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Spatial monitoring of the *Bremen Cog*

Long-term preservation of archaeological wooden ships in museums

Amandine Colson

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TABLE OF CONTENT

Foreword

This research was conducted as part of a three-years-doctoral fellowship funded by the German Maritime Museum (DSM), Leibniz Institute for Maritime History, in Bremerhaven (Germany). The goal set up by the institution was "to investigate the possibilities and limits of non-invasive documentation technologies to study long-term behaviours of large-scale museum objects; in cooperation with the engineering research field and the industry, in order to answer conservation-restauration issues."

Using 3D technologies to look at the deformation(s) on the *Bremen Cog*, 14th century-wooden vessel on display at the DSM, is an original idea from the author alone. After several years of 'standstill', the question of building an adequate support for the ship came back into the foreground and was discussed during a workshop organised by the museum in November 2013. All experts present agreed that nothing could be proposed without knowing more about the object's current conservation state. The structural weaknesses had to first be identified and understood in order to design the new support. Since wood can be considered as a 'living' entity, the question of deformation was essential, to slow down crack formation and anticipate breakage. Monitoring the geometry would help to understand all types of deformations involved in the process, for example seasonal changes as well as more linear and continuous deformation jeopardizing the structure over the long-term. This is how the journey began.

But it took several months for the idea to take root and become reality. Thanks to the participation of Dr. Ursula Warnke, former DSM director, the author was invited in early 2014 to the COST-Action "Colour and Space in Cultural Heritage" COSCH. This platform became an extraordinary opportunity to gain access to specialists and knowledge in the field of 3D technologies, and to be exposed to new ideas. The role of the COSCH in this project is significant and provided the impulse for the doctoral research. In September 2014, the *Bremen Cog* became a case study to test on three methodologies for acquiring the ship's deformation(s). Based on the feedbacks from several specialists attesting the scientific relevance of deformation monitoring on an archaeological ship, a doctoral fellowship was funded by the DSM between March 2016 and June 2019.

The very close collaboration with the Institute of Applied Photogrammetry and Geoinformatics (IAPG) from the Jade University of Applied Sciences, in the person of Professor Thomas Luhmann, head of the institute, and scientific staff member Heidi Hastedt, has impacted considerably this work.

Acknowledgments

Conducting this research has been an incredible journey, both professionally and personally.

First of all, I would like to thank my two supervisors: Professor Dr. Mona Hess, chair holder for Digital Technologies in Heritage Conservation, Otto-Friedrich University Bamberg and Professor Dr.-Ing. Habil. Dr. h.c. Thomas Luhmann, director of the Institute of Applied Photogrammetry and Geoinformatics (IAPG), at the Jade University of Applied Sciences in Oldenburg. They both believed in this topic and guided me throughout several years of research. I benefited from both their expertise and experience.

The work conducted on the *Bremen Cog* would have never been possible without the energy and knowhow of Heidi Hastedt, scientific staff member from the IAPG. She took time to answer my questions and was open to discuss every detail. Thanks to her dedication, we managed to overcome the challenges inherent to multidisciplinary research projects.

The Cost-Action COSCH supported three short-term-scientific-missions (STSM), which allowed me to get a first impression on how to acquire 3D data on the *Bremen Cog*.

I had the privilege to be funded for three years by the German Maritime Museum (DSM), Leibniz Institute for Maritime History, in Bremerhaven. Not only I was receiving a monthly salary (March 2016 to June 2019), but the museum supported all my travels, gave me the opportunity to participate in several scientific conferences and to meet many scholars.

The German Academic Exchange Service (DAAD) granted me a two-months scholarship, allowing me to spend time at the Museum of Cultural History, University of Oslo, Norway, and to work on the spatial monitoring of the Viking ship Oseberg.

Me, founding the European working Group ‘Monitoring of Preserved Ships’ (MoPS), was not only about building a network, but to exchange with sensational professionals, always keen on sharing their knowledge. A huge thanks is owed to David Hauer, my fellow PhD candidate from Oslo University, because we shared similar challenges. But also, thanks to Prof. Dr. Eleanor Schofield (Mary-Rose Trust) for her sense of humour, to Anders Algreen, Malin Sahlstedt and Håkan Thorén (Vasa Museum) for their sharp view on things, to Dr. Daniela Peloso (Ipso-Facto) for her enthusiasm, Marie-Laure Courboulès (Musée Départemental Arles Antique) for her vision on monitoring, to Dr. Toby Jones (Newport Medieval Ship) for his support on 3D documentation and to Dr. Pat Tanner for his expertise on ship building.

The last two years of the PhD were conducted while working part time as a conservator for the company denkmal3D. Hereby, I would like to thank Falk Näth and Volker Platen, my two amazing bosses, for their patience.
Mentoring has helped to structure my work and to cope emotionally with conducting this research. An enormous thanks to Dr. Bärbel Tress and her "PhD Success Lab", which I was lucky to participate to in summer 2020. I might have never finished this thesis without her advice.
Eduardo Cortina-Melendez was so kind to make the digital illustrations based on my sketches.
Reading and correcting a doctoral thesis is tedious and demanding. Without the precious help of colleagues and friends, sometimes prevented me from losing my mind. Thanks to Nico van Dyck for his comments on engineering, to John Hindmarch for the native speaker proof reading, to Tom Lenaerts for his precious comments, to Talip Törün and Gesa von Maydell for their English proof reading.
To the fencing club Bremen 1860 and all fencers, that helped me to stay physically almost in shape and moreover mentally sane.
At last, I owe my gratitude to my grandfather André Jardy (1929-2016) for passing me on the love for engineering and ships, and the persistence never to give up and to my godmother Marie Lessieux (1940-2014) who always saw how hard I could work to achieve my goals. She would have been so proud.
To my immediate family, Capucine Jardy-Colson, my mother, Jean-Michel Colson and Agata Piàtek, my father and stepmother, Lambert Colson, my brother, Lila Colson, my stepsister, Alice Foccroulle, my sister-in-law, as well as Ilia and Malo Colson, my niece and nephew, that were supporting me in their own ways often not knowing they did.
Thanks to my beloved husband Dr. Mike Belasus, who was by my side every single day and believed in me more than I did myself. He was the one keeping me afloat through all this time.
I am forever grateful to all the people not mentioned here, whom I have met at conferences and in private life. They inspired me to deliver the best scientific work I was capable of.
Finally, thanks to our little piece of paradise in the countryside, our home Groß Hollwedel, in Northern Germany, where the forest and the fields gave me the strength to complete this thesis.

Summary

Excavating, reconstructing, conserving, and presenting archaeological wooden ships is challenging and tedious. Such projects spread over several decades, costs a lot of money and involve specialists from many disciplines. When ships are finally presented in museums, the work is considered to be completed. But what about long-term preservation?

In Europe, almost 90 archaeological wooden ships and boats are on display in museums. Different conservation treatments exist, but the most commonly used is Polyethylene Glycol (PEG), at various concentrations and molecular weights, the result is a composite material made of wood and bulking agents with different structural and mechanical properties, depending on the preservation state. At the moment, very little is known about the long-term behaviour of such material. And yet, worrying deformations have been observed on several exhibited watercrafts, questioning the support and the presentation. Acquiring the ships' geometry or geometrical changes overtime would provide valuable information on the object's condition.

The current situation in museums is complex. A digital transformation occurs like elsewhere in society, focusing primarily on collection digitisation and increasing access to the objects remotely. On the other hand, specialists in preventive conservation debate on the fixed values on temperature and relative humidity and need data from 'real' life to show their effects on objects. Meanwhile, reducing air conditioning and heating aims not only to save money but also resources. Sustainability issues are indeed slowly integrated in museum reasoning. In this context, conservators' role remained unchanged: they are the guardians of ethics with an interdisciplinary education, struggling to become a research field and at the same time threatened to become theorists rather than practitioners.

Considering the context and the need for more data on the conservation state of archaeological wooden ships, the following research questions are addressed in this thesis: 1) How can deformation be monitored on archaeological wooden ships in museums over time and 2) how can geodetic measuring systems fulfil this purpose? 3) Can spatial monitoring be part of preventive conservation measures the same way climate monitoring already is? 4) What is needed in museums to allow conservators to integrate geodetic measuring systems into their workflow?

This dissertation aims to investigate geodetic measuring systems to monitor the geometry of archaeological wooden ships and evaluate the relevance of such a monitoring within preventive conservation. Furthermore, this thesis aims to embed geodetic measuring systems and corresponding workflows in the conservation-restoration practice to build a bridge between the two fields.

To begin with, the fundamental notions required to understand measuring and monitoring in three-dimensions, allows us to fill in the knowledge gap. Thereafter, the review presents existing initiatives on moveable cultural heritage, such as paintings, tapestry, and furniture. Subsequently, the four initiatives on archaeological wooden ships, which have been carried out worldwide so far, are presented in detail: the warship *Vasa* (1628) in Stockholm, Sweden, the flagship of Henry VIII *Mary-Rose* (1545) in Portsmouth, England, the roman barge *Arles-Rhône* 3 (1st c. AD) in Arles, France and the Viking ship from *Oseberg* (ca. 800) in Oslo, Norway.

The *Bremen Cog,* a medieval vessel discovered in Bremen in 1962, reconstructed, conserved and on display at the German Maritime Museum (DSM), is the central piece of this research and the case study. In 2001, after more than 20 years of conservation, the first deformations were observed, calling for "correction, stabilisation and presentation"[1]. Although, several surveys were conducted before, it is only in 2014, that the first sketches of a monitoring to investigate deformations took shape. Throughout different tests supported by the EU-COST-Action "Colour and Space in Cultural Heritage" from 2014 to 2016, the monitoring methodology and its goals matured slowly. The collaboration with the Institute of Applied Photogrammetry and Geoinformatics (IAPG) at the Jade University of Applied Sciences in Oldenburg, gave the scientific foundation to set up the final protocol.

Not only geodetic measuring systems offer the know-how to monitor deformations of archaeological wooden ships, but the mind-set has a lot in common with conservation of cultural heritage. Each step is carefully defined, which means great deal of self-criticism as well as questioning of one's own working processes and all complies to conservation ethics. Three archaeological ships are monitored using laser-based (*Vasa, Mary-Rose, Arles-Rhône 3*) and two using image-based measuring technologies (*Oseberg and Bremen Cog*). Every initiative collaborates with experts from Geodesy/Metrology. In Stockholm, the output from the monitoring enabled to reassess the performance of the air conditioning and lead to a change of equipment. In Portsmouth, adjustments were carried out on the support during the drying process thanks to the monitoring. In Arles, the monitoring already questions the choice to present the barge 'as sailing' because the wood tends to reverse to its *in-situ* shape. In Oslo, the ship's stability needs to be assessed before moving to the new museum. In Bremerhaven, information needs to be collected to design a new support system.

[1] Title of Per Hoffman's article in the International Journal of Nautical Archaeology (IJNA) in 2011

The comparison of the five initiatives working on spatial monitoring of archaeological wooden ships in museums shows that geodetic measuring systems give relevant output for long-term preservation. Thereupon, spatial monitoring needs to be integrated, before, during and after conservation, as monitoring changes of geometry should be part of the condition assessment. Based on the experience gathered on the *Bremen Cog* and observation made on the other initiatives, a workflow is proposed to help other professionals with the design of a spatial monitoring protocol.
In conclusion, it can be said that spatial monitoring still needs to reach more awareness among conservators but moreover among stakeholders. Additionally, capacity should be built on the necessary infrastructure in museums, such as the required expertise and equipment. Notions and basics from the field of Geodesy and Metrology should be added into conservation curricula, as well as lifelong training possibilities should be created for active conservators. Spatial monitoring offers many opportunities in preventive conservation and has the potential to be applied to other large-scale museum objects.

Zusammenfassung

Ausgrabung, Wiederaufbau, Konservierung und Präsentation von archäologischen Holzschiffen ist herausfordernd und mühsam. Solche Projekte dauern mehre Jahrzehnte, kosten viel Geld und beziehen Spezialisten aus vielen Disziplinen mit ein. Wenn die Schiffe schließlich in Museen präsentiert werden, gilt die Arbeit in der Regel als abgeschlossen. Aber wie sieht es mit der langfristigen Erhaltung aus?

In Europa sind fast 90 archäologische Wasserfachzeuge in Museen ausgestellt. Es gibt verschiedene Konservierungsmethoden, aber am häufigsten ist die Anwendung von Polyethylenglykol (PEG) in verschiedenen Konzentrationen und Molekulargewichten. Das Ergebnis ist ein Verbundmaterial aus Holz und Konservierungsmittel mit unterschiedlichen strukturellen und mechanischen Eigenschaften, je nach Erhaltungszustand. Über das Langzeitverhalten eines solchen Materials ist derzeit noch sehr wenig bekannt. Dennoch wurden bereits an mehreren ausgestellten Schiffen besorgniserregende Verformungen festgestellt, die das Stützsystem und die Präsentation in Frage stellen. Die Erfassung der Schiffsgeometrie oder geometrischer Veränderungen im Laufe der Zeit würde wertvolle Information über den Zustand des Objekts liefern.

Die aktuelle Situation in Museen ist komplex. Der digitale Wandel vollzieht sich wie überall in der Gesellschaft und konzentriert sich in erster Linie auf die Digitalisierung der Sammlungen und die Verbesserung des Fernzugriffs auf die Objekte. Auf der anderen Seite debattieren die Fachleute der präventiven Konservierung über die festgelegten Werte für Temperatur und relativer Luftfeuchtigkeit und benötigen Daten aus dem ‚wirklichen' Leben, um deren Auswirkungen auf die Objekte aufzuzeigen. In der Zwischenzeit zielt die Reduzierung von Klimaanlagen und Heizungen in Museen nicht nur auf eine finanzielle Ersparnis, sondern auch von Ressourcen ab. Fragen der Nachhaltigkeit werden in der Tat langsam in die Überlegungen der Museen integriert. In diesem Zusammenhang blieb die Rolle der Restauratoren unverändert: Die Hüter der Ethik mit einer interdisziplinären Ausbildung, die darum kämpfen, ein Forschungsfeld zu werden, aber gleichzeitig davon bedroht sind, verstärkt zu Theoretikern als Praktiker zu werden.

Auf Grund dieser Tatsache und des Bedarfs an mehr Daten über den Erhaltungszustand archäologischer Holzschiffe werden in dieser Doktorarbeit folgende Forschungsfragen behandelt: 1) Wie können Verformungen an archäologischen Holzschiffen in Museen langfristig überwacht werden und 2) wie können geodätische Messsystem diesen Zweck erfüllen? 3) Kann ‚Spatial Monitoring' Teil präventiver Konservierungsmaßahmen sein, so wie es etwa das Klimamonitoring bereits ist? 4) Was wird in Museen benötigt, damit Restauratoren geodätische Messsystem in ihren Arbeitsablauf integrieren können?

Ziel dieser Dissertation ist es, geodätische Messsysteme zur Überwachung der Geometrie von archäologischen Holzschiffen zu untersuchen und die Relevanz eines solchen Monitorings innerhalb der präventiven Konservierung zu bewerten. Darüber hinaus zielt dieser Arbeit darauf ab, geodätische Messsysteme und entsprechende Arbeitsabläufe in die konservatorische-restauratorische Praxis einzubetten, um eine Brücke zwischen den beiden Bereichen zu schlagen.

Zunächst werden die grundlegenden Prinzipien erläutert, die für das Verständnis der dreidimensionalen Messung und Überwachung erforderlich sind, um die Wissenslücke zu schließen. Danach werden bestehende Initiativen zu mobilem Kulturgut wie Gemälden, Wandteppichen und Möbeln vorgestellt. Anschließend werden die vier bisher weltweit durchgeführten Initiativen zu archäologischen Holzschiffen im Detail präsentiert: das Kriegsschiff *Vasa* (1628) in Stockholm/Schweden, das Flaggschiff von Heinrich VIII. *Mary-Rose* (1545) in Portsmouth/England, der römische Lastkahn *Arles-Rhône 3* (1. Jh. n. Chr.) in Arles/ Frankreich und das Wikingerschiff von *Oseberg* (ca. 800) in Oslo/Norwegen.

Die Bremer Kogge, ein 1962 in Bremen entdecktes mittelalterliches Schiff, das rekonstruiert, konserviert und im Deutschen Schifffahrtsmuseum (DSM) ausgestellt wurde, ist das Kernstück dieser Forschung und die Fallstudie. Im Jahr 2001, nach mehr als 20 Jahren Konservierung, wurden die ersten Verformungen festgestellt, die eine "Korrektur, Stabilisierung und Präsentation"[2] erforderlich machten. Obwohl zuvor mehrere Vermessungen durchgeführt wurden, entstanden 2014 die ersten Skizzen eines Monitorings zur Untersuchung von Verformungen. Während verschiedener Tests, die von der EU-COST-Action "Colour and Space in Cultural Heritage" von 2014 bis 2016 unterstützt wurden, reifte die Monitoring-Methodik und ihre Ziele langsam heran. Die Zusammenarbeit mit dem Institut für Angewandte Photogrammetrie und Geoinformatik der Jade Hochschule in Oldenburg lieferte die wissenschaftliche Grundlage für die Erstellung des endgültigen Protokolls.

Geodätische Messsysteme bieten nicht nur das Knowhow, um Verformungen von archäologischen Holzschiffen zu überwachen, sondern auch die denkmalpflegerische Denkweise. Jeder Schritt wird durchdacht und ein hohes Maß an Selbstkritik sowie das Hinterfragen der eigenen Arbeitsprozesse entsprechen der Konservierungsethik. Drei archäologische Schiffe werden mit laserbasierten (*Vasa, Mary-Rose, Arles-Rhône 3*) und zwei mit bildbasierten Messverfahren (*Oseberg und Bremer Kogge*) überwacht. Jede Initiative arbeitet mit Experten aus der Geodäsie/ Metrologie zusammen.

[2] Titel von Dr. Per Hoffmans Artikel in Restauro 2010

In Stockholm ermöglichten die Ergebnisse der Überwachung eine Neubewertung der Leistung der Klimaanlagen und führten zu einem Austausch der Geräte. In Portsmouth wurden dank der Überwachung Anpassungen an der Stützung während des Trocknungsprozesses vorgenommen. In Arles stellt die Überwachung bereits jetzt die Entscheidung in Frage, den Lastkahn "wie segelnd" zu präsentieren, da das Holz dazu neigt, sich in seine *in-situ*-Form zurückzulegen. In Oslo muss die Stabilität des Schiffes vor dem Umzug bewertet werden. In Bremerhaven müssen Informationen gesammelt werden, um ein neues Stützsystem zu entworfen.
Der Vergleich der fünf Initiativen, die sich mit der ‚Spatial Monitoring' von archäologischen Holzschiffen in Museen beschäftigen, zeigt, dass geodätische Messsysteme relevante Ergebnisse für die langfristige Erhaltung liefern. Daraufhin muss ‚Spatial Monitoring' vor, während und nach der Konservierung integriert werden, da die Überwachung von Geometrieveränderungen als Teil der Zustandsbewertung sein sollte. Auf Grund der mit der Kogge gesammelten Erfahrungen und der bei anderen Initiativen gemachten Beobachtungen wird ein Arbeitsablauf vorgeschlagen, der anderen Fachleute bei der Gestaltung eines ‚Spatial Monitorings' helfen soll.
Zusammenfassend kann gesagt werden, dass das Bewusstsein für ‚Spatial Monitoring' bei den Restauratoren, aber auch unter den entsprechenden Interessenvertretern noch geschärft werden muss. Zusätzlich sollten die Kapazitäten für die benötigte Infrastruktur in den Museen, wie z.B. das erforderliche Fachwissen und die Ausrüstung, aufgebaut werden. Begriffe und Grundlagen aus dem Bereich der Geodäsie und Metrologie sollten in die Lehrpläne der Restauratoren aufgenommen werden und es sollten Möglichkeiten für lebenslanges Weiterbildung für aktive Restauratoren geschaffen werden. ‚Spatial Monitoring' bietet viele Möglichkeiten in der präventiven Konservierung und hat das Potenzial, auch auf andere große Museumsobjekte angewendet zu werden.

Résumé

Fouiller, reconstruire, conserver et présenter des navires en bois issus de contexte archéologique est une entreprise difficile et fastidieuse. Ces projets s'étalent sur plusieurs décennies, coûtent beaucoup d'argent et requièrent les compétences de nombreuses disciplines. Lorsque les navires sont enfin présentés dans les musées, le travail est considéré comme achevé. Mais qu'en est-il de la préservation à long terme ?

En Europe, plus de 90 bateaux issus de contexte archéologique sont présentés dans des musées. Il existe différents traitements de conservation, mais le plus utilisé reste le Polyéthylène Glycol (PEG), ce à des concentrations et des poids moléculaires variés, et le résultat final est un matériau composite bois/consolidant dont les propriétés mécaniques sont variables en fonction du niveau de dégradation du bois. À l'heure actuelle, on sait très peu sur le comportement à long terme de ces matériaux. Pourtant, des déformations inquiétantes ont été observées sur plusieurs embarcations exposées, remettant en cause le support et la présentation. L'acquisition de la géométrie des bateaux ou des changements géométriques dans le temps fournirait des informations précieuses sur l'état de l'objet.

La situation actuelle dans les musées est complexe. Une transformation numérique s'opère comme ailleurs dans la société, se concentrant principalement sur la numérisation des collections et l'augmentation de l'accès aux objets à distance. D'autre part, les spécialistes de la conservation préventive débattent des valeurs fixes de température et d'humidité relative et ont besoin de données provenant de la vie "réelle" pour montrer leurs effets sur les objets. Par ailleurs, la réduction de la climatisation et du chauffage vise non seulement à économiser de l'argent, mais aussi des ressources. Les questions de durabilité sont en effet peu à peu intégrées dans le raisonnement des musées. Dans ce contexte, le rôle des restaurateurs reste inchangé : ils sont les gardiens de l'éthique avec une formation interdisciplinaire, luttant pour devenir un domaine de recherche et menacés en même temps de devenir des théoriciens plutôt que des praticiens.

Compte tenu du contexte et de la nécessité de disposer de plus de données sur l'état de conservation des navires archéologiques en bois, les axes de recherche suivants sont traités dans cette thèse : 1) Comment la déformation des navires archéologiques en bois dans les musées peut-elle être suivie dans le temps et 2) comment les systèmes de mesure géodésique peuvent-ils remplir cette fonction? 3) Le suivi 3D peut-il faire partie des mesures de conservation préventive, comme c'est déjà le cas pour le suivi environnemental ? 4) Que faut-il faire dans les musées pour permettre aux restaurateurs-conservateurs d'intégrer les systèmes de mesure géodésique dans leur travail ?

Cette thèse a pour but d'étudier les systèmes de mesure géodésique pour contrôler la géométrie des navires archéologiques en bois et d'évaluer la pertinence d'un tel suivi 3D (spatial monitoring) dans le cadre de la conservation préventive. De plus, cette thèse vise à intégrer les systèmes de mesure géodésique et les processus de travail correspondants dans la pratique de la conservation-restauration afin de créer un pont entre les deux domaines.
Dans un premier temps, les notions fondamentales nécessaires pour comprendre la mesure et le suivi en trois dimensions nous permettent de combler le manque de connaissances. Ensuite, l'étude présente les initiatives existantes pour le patrimoine culturel mobilier, tel que les peintures, les tapisseries et les meubles. Puis, les quatre initiatives sur les navires archéologiques en bois, qui ont été menées mondialement à ce jour, sont présentées en détail : le navire de guerre *Vasa* (1628) à Stockholm, Suède, le navire amiral d'Henri VIII *Mary-Rose* (1545) à Portsmouth, Angleterre, la barge romaine *Arles-Rhône 3* (1er siècle après J.-C.) à Arles, France et le navire viking d'*Oseberg* (env. 800) à Oslo, Norvège.
La *Cogue de Brême,* navire médiéval découvert à Brême en 1962, reconstruit, conservé et exposé au musée maritime allemand (DSM), est la pièce maîtresse de cette recherche et l'étude de cas. En 2001, après plus de 20 ans de conservation, les premières déformations ont été observées, nécessitant "correction, stabilisation et présentation"[3]. Bien que plusieurs études aient été menées auparavant, ce n'est qu'en 2014 que les premières esquisses d'un suivi des déformations ont pris forme. Au cours de différents tests soutenus par l'action EU-COST "Colour and Space in Cultural Heritage" de 2014 à 2016, la méthodologie de suivi et ses objectifs ont lentement mûri.
La collaboration avec l'institut de photogrammétrie appliquée et de géo-informatique (IAPG) de l'université des sciences appliquées de Jade, à Oldenburg, a fourni la base scientifique nécessaire à la mise en place du protocole de suivi final.
Les systèmes de mesure géodésique offrent non seulement le savoir-faire nécessaire au suivi des déformations des navires archéologiques en bois, mais l'état d'esprit a beaucoup en commun avec la conservation-restauration du patrimoine. Chaque étape est réfléchie et l'autocritique ainsi que la remise en question de ses propres méthodes de travail sont conformes à la déontologie de la conservation. Trois navires sont suivis via des technologies laser (*Vasa, Mary-Rose, Arles-Rhône 3*), et les deux autres basées sur l'image (*Oseberg et Cogue de Brême*). Chaque initiative a collaboré avec des experts en géodésie/ métrologie.

[3] Traduction du titre de l'article de Per Hoffmann 2011 publié dans l'International Journal of Nautical Archaeology (IJNA) en 2011hy

À Stockholm, les résultats ont permis d'évaluer la performance de la climatisation menant à une optimisation de l'équipement.
À Portsmouth, des ajustements du support ont pu être effectués durant le séchage. À Arles, le suivi remet d'ores et déjà en question le choix de la présentation « en position de navigation » et montre que le bois à tendance à revenir à sa forme *in-situ*. À Oslo, la stabilité du bateau est en cours d'évaluation en vue de son déplacement dans le nouveau musée.
À Bremerhaven, les informations sont en cours de collecte afin de pouvoir concevoir un nouveau support.
Comparer ces cinq initiatives de suivi 3D (spatial monitoring) des navires archéologiques en bois dans les musées a permis de montrer que les systèmes de mesure géodésique donnent des résultats pertinents pour la conservation à long terme. Ainsi, le suivi 3D (spatial monitoring) devrait être intégré avant, pendant et après la conservation afin de suivre l'état de conservation et les changements de géométrie. Basé sur l'expérience de la *Cogue de Brême* et les observations faites dans le cadre d'autres initiatives, un processus de travail a pu être proposé pour aider d'autres professionnels à la conception d'un suivi 3D (spatial monitoring).
En conclusion, le suivi 3D (spatial monitoring) doit encore faire l'objet d'une plus grande sensibilisation auprès des conservateurs-restaurateurs, mais aussi du personnel décisionnaire. De plus, les moyens doivent être développées en ce qui concerne l'infrastructure dans les musées, telle que l'expertise et l'équipement nécessaire. Les notions fondamentales de géodésie et de métrologie doivent être intégrées aux formations initiales en conservation-restauration et des formation continues dédiés aux praticiens actifs devraient être créées. Le suivi 3D (spatial monitoring) offre de nombreuses options en matière de conservation préventive et peut être appliqué à d'autres objets muséaux de grandes dimensions.

1 INTRODUCTION

When the German Maritime Museum[4] (DSM) in Bremerhaven organised consultations in 2013 on a new *Bremen Cog* permanent exhibition, the aspect of presentation was central. Neither historian, nor archaeologists, curators, conservators, nor representatives of the cultural heritage protection office, were satisfied with the situation. The flagship of the Hanseatic League and the best-preserved cargo ship in north-western Europe from the medieval period was laying on a forest of 'metal rods' since 2006. Not only the aesthetic was not satisfying, but the support was absolutely inadequate for the ship (see cover picture). However, it was not surprising since the metal rods were never designed to become a support and to stay that long in place, when they were installed. Like it is often the case, the short-term solution turned into a long-term one.

But before any effort could be put into a new support, the deformations and movements described by Dr. Per Hoffmann[5] had to be captured and studied to enable the design of an appropriate 'tailored' solution. The cost for such a support were pre-estimated around 1,5 million euros, only for the material costs[6]. Such investment must be carefully planned and thought through.

The idea of a 'deformation monitoring', later 'spatial monitoring', emerged from the need of an optimized presentation of the 14th century ship and came from the author herself. The goal was to find the best solution within the museum's 'Cog Hall'[7], where the ship has been reconstructed, conserved and is on display today.

1.1 Problem statement

1.1.1 Waterlogged wood

Only a combination of the right climate and a singular preservation environment such as bogs or other types of wetlands, as well as an underwater context, enables the necessary anaerobic conditions to preserve organic material over time. The discovery of wood in archaeology is rare, and therefore always very special. No archaeological wood can be presented in a museum without conservation (Hoffmann, 2013, pp. 3–5). The degradation of cell walls in the wood leads to their collapse and shrinkage during uncontrolled drying processes. Without conservation the object would not remain recognisable, lose its function and any interpretation would become impossible as well as further archaeological studies.

[4] Deutsche Schifffahrtsmuseum (DSM) – Leibniz-Institut für Maritime Geschichte, Bremerhaven
[5] Head of Conservation (1979-2008) at the German Maritime Museum
[6] Unofficial estimation from an engineer office in Bremerhaven
[7] Kogge Halle, official name for the room hosting the ship

Archaeological wood has been conserved since the 1860's (Florian, 1990) but it took a massive turn in the 1940's with the introduction of polymers, such as polyethylene glycol (PEG).

At first tested on small objects, the application of PEG on large wooden artefacts such as ships has changed the conservation of waterlogged organic material forever. Three pioneer projects implied a significant step forward in the 1960's with: the warship *Vasa* (see 4.3.2, p. 88), *Skudelev* ships[8], and the *Bremen Cog*, discussed in detail in chapter 5, p. 105, and all conserved with PEG. Although other methods exist, PEG treatments continue to be very often the first choice internationally. Per Hoffmann[9] even dedicates a chapter of his book "Conservation of Archaeological Ships and Boats" to choosing the right method to conserve waterlogged wood (Hoffmann, 2013, pp. 121–135).

The conservation is conducted in different ways, the PEG concentration can vary from 40 to 70 %, depending on the method used. However, one thing is certain: after the treatment, the material is not wood anymore, but a combination of wood and polymer. The long-term behaviour of this new compound is not yet well known.

Wood is a hygroscopic material, which means that it is subject to moisture. For that reason, moisture content* (MC) is a very important parameter to understand the material's behaviour, its mechanical and physical properties. Since each wood species reacts differently, variations are evaluated through the antishrink efficiency* (ASE) (Ibach, 2010, p. 12).

1.1.2 Societal and political impact

A ship in an archaeological context is a rarity and therefore always exceptional for both the archaeologist and the public. The preservation of ship finds is *"unique"* and must be understood within its own political and historical context (Belasus, 2017).

Benefiting from global awareness, all these projects attract great interest, and thus extensive funding is often allocated both to excavate and conserve, in order to one day present these finds in museums. The decision to preserve these ships is never taken by chance, as 'ships' always represent a certain 'prestige'. All stakeholders were aware of the challenges upfront, as well as the extremely long duration of such projects. For instance, the three experts[10] consulted to set up a conservation plan of the *Bremen Cog* estimated the treatment duration from 20 up to 30 years (see 5.1.2 Conservation and presentation p. 109).

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[8] So-called Roskilde ships, Viking Ship Museum, Roskilde, Denmark. Excavation summer 1962

[9] Dr. Per Hoffmann, wood chemist former Head of Conservation at the German Maritime Museum, Bremerhaven (1979-2008)

[10] Prof. Walter Liese, Prof. Detlef Noack and Prof. Hans-Hermann Dietrich – University of Hamburg

Although many of these experiments were being conducted for the first time, no one advanced blindly by passively undergoing the different stages. It is without any doubt, that projects of this magnitude can only be the result of a clear political commitment.

1.1.3 Long-term preservation

Generally, there are four phases in a project dealing with the preservation of archaeological ships: 1) Excavation/Salvage; 2) Reconstruction; 3) Conservation; 4) Presentation. Where 2) and 3) can be conducted in a different order (see Figure 1-1). But when the ships are considered stable and presented in museums, preserving them is not trivial. The aim is to care for a composite object made of wood and consolidant, and this includes all efforts conducted beyond conservation. One can also describe this as a permanent maintenance care, here called phase 5) long-term preservation (Colson et al., 2022a). Unfortunately, the post-conservation phase is not always considered carefully enough or even completely ignored, and therefore not budgeted. For instance, there is absolutely no mention of such tasks included in the project planning for the *Bremen Cog* beyond the set-up of the permanent exhibition.

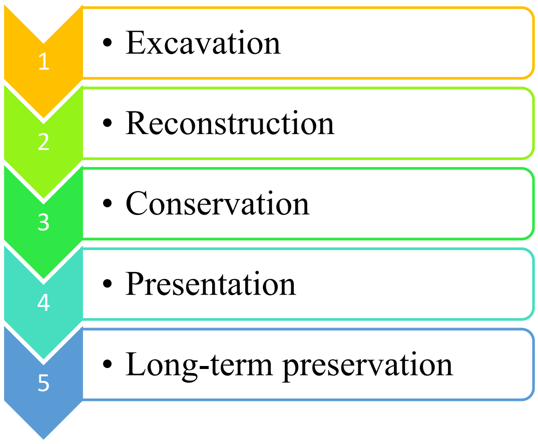

Figure 1-1: Workflow archaeological ship projects (A. Colson)

It was assumed that these ships would require little care after the completion of the conservation treatment and the installation of a support. Experience shows that this assumption was wrong (see 4.3 Spatial monitoring of archaeological ships p. 85).

For this reason, no resources – people, equipment, or materials– are allocated. Museum conservators find themselves in a delicate situation, having no capacity to take care of any such ‘unexpected issues’ occurring on archaeological ships, when they must oversee a whole collection and not just a single artefact.

1.1.4 Museum presentation

Ships are considered to be moveable[11] cultural heritage (UNESCO, 2017). Although, in reality a ship will rarely be moved from its original location once installed in the museum's exhibition, making it somewhat immovable[12]. In practice, this means that museum staff are dealing with a 'theoretically' movable objects of large scale, that do not fit into a laboratory. Consequently, every task must be conducted inside the exhibition and sometimes during the museum's opening hours. In permanent exhibitions the challenge is to keep a stable climate considering the visitor's traffic in the museum. Any operation must take all these constraints into account, which often causes logistical challenges, using lifting platforms, scaffolding and other support methods. Additionally, the safety of staff and visitors must be ensured at all times.

Most ships in museums are presented 'in function' or as if they would be ready to embark on another journey. Ships or boats found distorted during excavation are conserved and reshaped to fulfil this requirement (Hoffmann, 2013, p. 141). All ships mentioned in this dissertation share this presentation bias (see 4.3 Spatial monitoring of archaeological ships p. 85). On the other hand, any boat builder will think twice about leaving a wooden boat in a drydock for more than six months without any proper support. It is considered too risky for the hull to distort and would affect the boat's performance on the water[13]. This fact points out that even a boat made of modern wood has issues when stored on land for too long.

1.2 Terminology

1.2.1 Conservation documentation

Cultural heritage objects are permanently documented. Almost every guideline or code of ethics related to cultural heritage and its conservation mentions documentation.

The definition from the Oxford dictionary refers to the formal aspect of documentation:

> *Documentation (noun): material that provides **official information** or evidence or that **serves** as a **record**.*
>
> *Document (verb): record something in written, photographic or other form.*
>
> (Soanes and Stevenson, 2005a)

[11] Property which, on religious or secular grounds, is specifically designated (...) as being of importance for archaeology, prehistory, history, literature, art or science.

[12] Monuments, (...), which are of outstanding universal value from the point of view of history, art or science; groups of buildings, (...); and sites.

[13] Personal communication with Dr. Pat Tanner, traditional wooden boat builder, Cork, Ireland

In certain contexts, the term is legally binding and linked to 'evidence'. The other interesting aspect, however, is the origin of the word deriving from the Latin *Documentum* for 'proof'. Tracing the intrinsic meaning of 'documentation' leads ultimately to the term 'record':

> Record (verb): set down in **writing** or some other **permanent form** for later reference; (noun) a thing constituting an **evidence about the past** (..) *(Soanes and Stevenson, 2005a)*

The documentation process can be described in three "stages": 1) all primary evidence linked to an object, a kind of ID; 2) condition reports or the object's health; and 3) intervention reports or all actions undertaken on and around the object, as a kind of activity report. An overview of all different kinds of documentation has been described by Michelle Moore (Moore, 2001).

In the UNESCO[14] handbook #3 for cultural heritage protection, Matthew Stiff lists all basic information necessary for the inventory such as the mention of: ownership, material, storage location (Stiff, 2007). The guidelines published by the German museum association[15] in cooperation with ICOM Germany, use 'documentation' in the sense of information related to interpretation in a historical, artistic or archaeological context (Arbeitsgruppe 'Standard für Museen' 2006, 14). This notion is also referred to as 'primary evidence' and available to all professionals around the object.

The condition report consists of collecting facts about the object's state of preservation also called examination. Any change of colour, dimension, signs of damage, cracks or other alteration should be recorded. The storage conditions can also be part of such reports, e.g., type of building facility, temperature, relative humidity. The aim is to enable a conservator to reconstruct the origin of a degradation and thus isolate the responsible parameter(s).

Establishing a diagnosis is the first step before a treatment plan. All technical or analytical reports are included in that section, e.g., results of material analyses or dating. This step is linked to the ethical obligation of a conservator to justify every decision. Article 16 of the Charter of Venice describes how important documentation is (ICOMOS, 1964).The code of ethics from the American Institute for Conservation of Historic and Artistic Works (AIC) specifies that after the condition report, comes the proposal or treatment plan part of the intervention report (American Institute for Conservation of Historic and Artistic Works, 2015). The intervention report is described in the code of ethics from the European Confederation of Conservator-Restorer Organisation (ECCO). In Article 10 it is noted that all documentation is part of the object's record file (European Confederation of Conservator-Restorers' Organisations, 2003).

[14] United Nations Educational, Scientific and Cultural Organization

[15] Deutscher Museumsbund

In that section, the practitioner and all material used need to be stated, as well as date and duration of each performed treatments.
At the beginning of the 21st century guidelines or code of ethics were updated or revised, e.g., AICCM[16] 2002, ECCO 2003, AIC 2015, CAC-CAPC[17] 2009. However, as Jonathan Ashley-Smith pointed out correctly, the two biggest organisations in charge of conservation, IIC[18] and ICOM-CC[19], do not provide any ethical guidelines and no definition of a specified 'conservation documentation' (Ashley-Smith, 2017).
As Michelle Moore points out: *"There are as many ways to document conservation work as there are situations when data should be documented"* (Moore, 2001). Although every institution or practitioner individualises how they record conservation, there are essentially two methods: *"textual or visual"*, Moore continues. Notably, there is no mention of digital photography, except in the AIC Guide (American Institute for Conservation of Historic and Artistic Works, 2017). This document is dedicated exclusively to digital photography and conservation documentation. Several related methods are listed: infrared (IR) and ultraviolet (UV) photography, UV-VIS-IR combined, as well as multispectral and hyperspectral imaging, but nothing is mentioned about three dimensions recording.
The European treaty, so-called Granada Convention, signed in 1985, dealing with architectural heritage, mentions 'new technologies' as alternatives for recording (see the Article 17 paragraph 3) (Council of Europe, 1985).
Other than that, the absence of any reference to new technologies or digital documentation methods in any policy should be mentioned here.
Interestingly, certain guidelines exist on how to manage and store digital documentation but not how about it should be conducted. Here the UNESCO charter and guidelines, as well as the London Charter should be mentioned (UNESCO, 2003) (UNESCO, 2016a) (Denard, 2012).
The last aspect of conservation documentation is to contribute to the optimization of methods and the development of this profession. This relationship between documentation and the "*profession's body of knowledge*" is referred to by the ECCO and seen as an *"obligation to colleagues and the profession"* under article 23, rather than a contribution (European Confederation of Conservator-Restorers' Organisations, 2002).

[16] Australian Institute for Conservation of Cultural Material (AICCM)
[17] Canadian Association for Conservation of Cultural Property and of the Canadian Association of Professional Conservators CACCP-CAPC
[18] International Institute for Conservation of Historic and Artistic Works
[19] International Council of Museums –Committee for Conservation

1.2.2 Preventive conservation

Stefan Michalski[20] identifies nine agents responsible for deterioration: physical forces, fire, pests, thieves and vandals, water, pollutants, inadequate relative humidity, light, inadequate temperature (Michalski, 2004). Sometimes a tenth point is also mention: negligence. These different threats need to be either controlled or completely avoided.

Conservation of cultural heritage is based on ethics and central to every practice. A few principles and concepts are fundamental such as reversibility, authenticity, life cycle of objects, the need to find a compromise and minimizing intervention to prioritise prevention (Janis, 2005) (Muñoz Viñas, 2002). In order to preserve its integrity, the aim is to find a way to 'not act' on the object, which leads ultimately to recommend preventive measures. The Canadian code of ethics goes even further and states preventive conservation as the *"primary objective"* of conservation professionals (Canadian Association for Conservation of Cultural Property and of the Canadian Association of Professional Conservators, 2000, p. 6). The European code of ethics also gives priority to preventive conservation over treatment in Article 8 (European Confederation of Conservator-Restorers' Organisations, 2003).

Preventive conservation has been conducted unconsciously since people began collecting objects. Chris Caple[21] draws the history of preventive conservation, as an introduction to his book (Caple, 2011). However, the term 'preventive conservation' only started to be systematically used in the 1970's (Lambert, 2014). Caple simply defines preventive conservation as *"any measure that reduces the potential for or prevents damage"* to cultural heritage collections (Caple, 2011).

At the Getty Conservation Institute (GCI), preventive conservation is considered as the *"most efficient form of conservation"*, following four stages: 1) identify the threat(s); 2) verify risk; 3) cost-efficient means to measure risk; 4) develop method to reduce or eliminate the risk.

The AIC core document gives a very clear description of preventive conservation:

> "Guideline 20 - Preventive conservation: the conservation professional should recognize the critical importance of preventive conservation as the most effective means of promoting the long-term preservation of cultural property. The conservation professional should provide guidelines for continuing use and care, recommend appropriate environmental conditions for storage and exhibition, and encourage proper procedures for handling, packing and transport."

[20] Retired Senior Conservation Scientist, Canadian Conservation Institute, Ottawa, Canada

[21] Emeritus Reader in Archaeological Conservation, Durham University, UK

> "Commentary 20 - Preventive Conservation is the mitigation of deterioration and damage to cultural property through the formulation and implementation of policies and procedures for the following: appropriate environmental conditions; handling and maintenance procedures for storage, exhibition, packing, transport, and use; integrated pest management; emergency preparedness and response; and reformatting/duplication. Preventive conservation is an ongoing process that continues throughout the life of cultural property, and does not end with interventive treatment.
>
> (American Institute for Conservation of Historic and Artistic works, 2015)

The methods used to perform preventive conservation are varied, but as noted for documentation (see 1.2.1, p. 28), the choice is left to the discretion each professional.

1.2.3 Spatial monitoring

The term monitoring is used in many different contexts: but what does it mean? Moreover, how is it understood here?
In the dictionary entry 'monitoring' is defined as follows:

> "Monitoring: Observe and check the **progress or quality** of (something) over a period of time; keep under **systematic review**" or "Maintain **regular surveillance** over". (Soanes and Stevenson, 2005b)

Interestingly the notion of change is present in the definition in 'progress or quality', which gives a timeframe. The methodology is also underlined by 'systematic review', suggesting an action planned in consistent intervals.
No official definition of 'monitoring' could be found for the conservation field, but it gives a tangible form to all preventive conservation* measures.
The word's Latin origin gives us information about some additional level of understanding: *monitor* is also the person who warns, guides and advises (Gréco, 2016).
So, it appears that 'monitoring' is not only control and surveillance, checking what we already know, but can also help in collecting clues where we know too little. Actually, it reaffirms the core business of conservation: collection information for future interpretation and use.
At present, the term 'monitoring' is broadly used in conjunction with environmental issues, for example, collecting data on temperature, relative humidity, pollutants and pests in museums rooms and storage. The corresponding task is often referred to as 'climate monitoring' or 'environmental monitoring', considered as a basic requirement for all collection care. According to Susanne Keene only half of the museums were monitoring climate in the UK in the late 1980's (Keene, 2002, p. 121).

While ‘documentation’ (see 1.2.1, p. 28) includes assessing the object on a regular basis, the condition report, one could argue, is no longer documentation but already ‘monitoring’.

Going back to the object and the condition reports based on information collected overtime is a decisive step in planning further actions.

In fact, ‘condition report’ could be considered as a ‘time zero’ process, and all changes coming afterwards should be considered as part of the ‘condition monitoring’.

To be accurate, one should be more specific and distinguish between different types of monitoring, and their different aims.

The term ‘monitoring’ is used in engineering to describe the acquisition of observed natural or artificial phenomena over time. The point is to have a dynamic system, where it is possible to intervene to adjust parameters, if these do not match previous defined values. The aim is to detect deformations and find their origin, but also to collect evidence in case of damage (Wieser et al., 2017, pp. 7–8).

In this thesis, ‘spatial monitoring’ was chosen to describe the kind of work conducted by the author. On the one hand, it constitutes a clear distinction to other types of monitoring known in heritage science, on the other hand it is the same term used in engineering. The aim is to acquire the object’s geometry and refers to the object’s three-dimensions, specifically the change of shape occurring over time. Keeping an eye on geometrical changes, is the guarantee to avoid missing relevant information in order to preserve objects long-term.

1.2.4 Documentation vs monitoring

As clarified in paragraph 1.2.1 and 1.2.3, documentation and monitoring are two very different notions. Documentation is looking at the object globally and will include all aspects, from elementary to very detailed. It reaches a level of exactness that the surveyor needs and aims for according to her/his ultimate goals. Within a collection, documenting the object for the inventory, and proceeding to a condition report before enacting conservation measures, ensures the consistency, and enables better overall management. Standards must be followed, and methodology must be defined, but these can be optimized over time.

For ‘monitoring’, one focuses on single aspects, for example: gathering temperature or relative humidity. One parameter is singled out and the methodology is specified and defined precisely from the start to enable comparability. The specific value is isolated at first and later put into a global context during the analyses. The scientific reasoning and exactness required to set up monitoring is much more demanding than for the documentation.

Expectations are different, but both 'documentation' and 'monitoring' can be global and specific, whichever is conducted needs to have predefined goals. Using the example of climate monitoring again, the aim is to look at variations of temperature and relative humidity according to predefined values, and take action in adjusting the air-conditioning system.

From an engineering perspective a monitoring mostly focuses on one structure, but it can also look into manufacturing developments over time on several objects of the same type. The central notion is time.

The same approach is applied to 'spatial monitoring'. The idea is to look at three-dimensional changes that would lead to potential breakages, or deformation. Hopefully, monitoring the object over time, helps to predict the course of damage and enable preventive measures, such as adapting the support system. This method is integrated into risks management approach, which has already been integrated into preventive conservation over the last twenty years (Ashley-Smith, 1999).

1.3 Summary chapter 1

Organic materials are rarely found in an archaeological context, even more so for larger structures, which makes the discovery of ships and boats almost automatically a sensation for both for the archaeologists and the public. Without a conservation treatment such artefacts cannot be preserved. Apart from the polymers used, the staff and space needed for the treatment, generate high costs. Keeping in mind that such projects take several years, and sometimes up to several decades to be completed, the investment is enormous. Conserving archaeological ships is costly and time-consuming. Budgets usually cover: 1) excavation; 2) reconstruction; 3) conservation and 4) presentation; but beyond this point, no resources are allocated. Museums are then left in a delicate situation if anything unexpected happens.

Documentation in conservation is ethically binding. It includes the basic information on the object, the so-called primary evidence, the condition report or state before treatment, and the intervention report, such as any action conducted on the object. However, all practical aspects of the documentation as to which information will be collected and how this should be done, are left to the professional's discretion. Mention of digital photography or new technologies is rarely found in guidelines or reference documents.

The main goal of all conservation professionals is to avoid any action on the original.

For this reason, preventive conservation is always prioritised. Preventive conservation focuses on the objects' environment and collected data related to any associated risks. All potential threats should be avoided or controlled and monitored. However, changes to the geometry have so far not been described as part of a condition report, nor in condition monitoring.
This particular aspect is the focus of this thesis, and the term 'spatial monitoring' was chosen to express this aspect most accurately, since the same term is used in engineering.
In the light of the described research desiderata, the question of 3D documentation, spatial monitoring, are to be examined in chapter 3 AIMS AND DELIMITATION OF RESEARCH TOPIC p. 53.

1.4 Structural overview

In order to facilitate the reading of this work, an overview of how the thesis is structured is necessary. The text is organized as follows: after the introduction, the situation in museums is discussed as a means to place this research in the current context. There, the question of digitisation of museum collections, the on-going conservation debate, and the ecological sustainability, as well as the conservation profession in museum, are covered in broad terms. The goal is to understand in which environment museum conservators practice their trade, which necessarily impacts the solutions that are or need to be developed (2 BACKGROUND p. 37).
Chapter 3 sets up the research questions and aims. Additionally, the targeted audiences addressed by this thesis are listed (conservators, digital professionals in cultural heritage, decision and policy makers, and geodetic measuring engineers) and are as well shortly justified (3 AIMS AND DELIMITATION OF RESEARCH TOPIC p. 53).
The research state or state-of-the-art (4 STATE OF RESEARCH p. 65), is giving an overview of the basic knowledge needed to understand how to acquire three dimensions. Yet, the current initiatives working on spatial monitoring of archaeological ships are also summarized, which happened to be all located in Europe.
The Case Study of the *Bremen Cog* (5 CASE STUDY p. 105) is reporting on the issues encountered by a medieval wooden ship on display at the German Maritime Museum, Bremerhaven, and how the idea of a spatial monitoring emerged.

In the final chapter, the spatial monitoring systems applied to archaeological wooden ships in museums are reviewed. The lessons learned by author over the course of her research are aiming to show what mistakes could be avoided, followed by workflow recommendations and some suggestions explaining the difficulties to implement new workflows in conservation (6 CONCLUSIONS p. 139).

2 BACKGROUND

Spatial monitoring for the preservation of cultural heritage is almost exclusively performed by geodetic measuring systems on heritage buildings. Are conservators in museums reticent to the use of digital technologies or are they *"unsurprisingly conservative (and) (...) tend to be unadventurous, at least in public"* as Jonathan Ashley-Smith[22] claims (Ashley-Smith, 2017). Ashley-Smith's opinion is clear: too many rules are "*stifling the innovation, needed in a changing environment*", pointing out the professionalisation and specialisation of the field, which constitutes a very restrictive straitjacket.

But instead of labelling the conservators "*unadventurous*", let us look into their professional environment and the current challenges faced by museums.

The museum world is changing. This chapter summarises the current discussion that plays a decisive role in the implementation of digital technologies, and in particular geodetic measuring systems, as part of conservators' workflows. The aim is not to give an exhaustive overview of all aspects currently affecting museums, but to select and present the ones which appeared relevant over the course of this research as a general background. This should be seen as an 'ecosystem' in which conservators practice their profession.

2.1 Digitisation of museum collections

2.1.1 New era in museums

The digital era has entered the museum world, and the process of transformation has already been ongoing for three decades.

In the 1990's, the introduction of databases in collection management was a big change for inventories and afforded up many opportunities, e.g. providing access to knowledge, but it also introduced certain problems, e.g. the question of ownership (Keene, 1998, p. 3). Nowadays, almost everything is produced digitally: photographs, reports and exhibition catalogues, but also data related to temperature and relative humidity, as well as visitors' statistics etc. All the data being produced needs to be managed and structured, which is not a trivial task. Questions of short, middle and long-term access and storage of different data formats and their metadata are currently being discussed in museums yet the issue is still not completely solved (Keene, 2002, p 226).

'Digitisation' has become a central topic in society as well as in museums. The term is simply defined as the process of converting from analogue into digital form[23]. However, in cultural heritage organisations, digitisation can take various forms.

[22] Former Head of Conservation from the Victoria and Albert Museum, London, UK

[23] Oxford English Dictionary 2006

For instance, the aim can be to digitise artefacts or to create new interactive exhibits (Gries, 2019). But depending on the department, each museum professional will have their own objectives. The museum's education department will focus on engaging various audiences to keep the public interested, hoping to offer an exciting visit. The marketing department will build an online shop and hope for a sufficient number of visitors at the new temporary exhibition openings to buy their attractive selection of items. The public relation department will care for the online presence through social media channels in order to increase the number of visitors on the annual report. In fact, the 'digital' should be understood as holding a "*cross-sectional function*" [24] (Gries, 2016). The tasks related to digitisation are broad, which makes it hard for museum leaders to prioritise them (Deutscher Museumsbund, 2018). In this matter, institutions need support and guidelines. As an example, in Bavaria, the agency for non-state museums[25] advises museums and has a dedicated team focused exclusively on 'Digitisation/Inventory', indicating how complex the topic is.

2.1.2 Goals of collection digitisation

Yet when 'digitisation' concerns the collection, the first goal is to enable better access. The opportunity to transfer an artefact into a digital medium enables the resource to be easily copied and shared with others. Thus, collaborations with other institutes and scholars are made possible and hopefully new research projects can be generated. At the same time, showing their treasures can contribute to attracting more awareness from the media and consequently encourage the public to consider a visit. More interaction with the outside world also ensures greater presence in the local community, and subsequently to the surrounding schools and education stakeholders. Being one of the core missions of museums, digitisation contributes to education as well. But theoretically, collection digitisation also supports preservation, for example when fragile objects are handled less, or a facsimile can be produced for an exhibition while the original is kept in storage (Hughes, 2004, pp. 9–17). However, objects are rarely selected for a digitisation campaign based strictly on their preservation state, but rather for their historical or archaeological relevance, established by curators, where conservators have little to say. The essay by Andrew Prescott and Lorna Hughes criticises the lack of reflection from certain digitisation initiatives, implying that numerous digital surrogates engage only with scholars and with a very limited number of general users. For that reason, target audiences should be addressed directly (scholars, education professionals, policy makers etc…) and the outreach strategy defined accordingly.

[24] „Das Digital als Querschnittsfunktion" Dr. Christian Gries – Translation by A. Colson

[25] Landesstelle für nichtstaatlichen Museen in Bayern

Should the existence of such targets remain unknown, the original goal of increasing access is completely negated. The other aspect mentioned by Prescott and Hughes is the choice of technologies and how they are applied. The lack of 'detailed' planning reveals that certain artefacts, such as old manuscripts, were digitised using one single method that appeared to be suitable only for certain parts of the object, but not for others. (Prescott and Hughes, 2018).

The special issue from the ICOM Journal (Museum International) named "*Museums in a digital World*", published in 2018, shows how central the discussion is. In the editorial it is clearly stated that the main role of collection digitisation is to engage with the public and create online content in order to attract more visitors (Mac Devitt, 2018). This is confirmed by a European survey conducted in 2020, showing that more than 80% of museums' primary goal with collection digitisation is to increase "*their visibility*" (NEMO, 2020). To illustrate this trend, a very good example is *museum4punkt0* at the Stiftung Preußischer Kulturbesitz in Berlin. The collaborative project is focusing on communication and outreach using digital technologies to support *"the narratives of curators, scientists or the public"* (Glinka, 2018). New technological and methodological insights are being considered, as well as new applications for education, visitor's interaction, and participation. The project was launched in 2017, initially for three years, and funded by the Federal Government Commissioner for Culture and the Media[26] with 15 million Euros[27]. In 2020, the funding was extended by 10 million Euros, supported by the German Federal Parliament[28].

Many other projects exist that are not stated here. However, the point is to acknowledge that the goal of collection digitisation is not long-term preservation and that conservators are not actively involved in the process, or at least not as the driving force.

2.1.3 Choice and process of digitisation

Although the goal seems to be engaging with the public, very few museums have a digitisation strategy. According to the report ENUMERATE Core Survey conducted for the European Union, 77% of museums had a digital collection or were conducting activities related to digitisation of their collections, but only 45% had a corresponding written digitisation strategy (Nauta et al., 2017). The statistics were based on data collected from 2011 to 2017 in museums, libraries, and archives in 36 countries[29] based in the European Union and elsewhere.

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[26] Die Beauftragte der Bundesregierung für Kultur und Medien

[27] https://www.museum4punkt0.de/news/museum4punkt0-startet-ideenlabor-fur-digitale-anwendungen-in-deutschen-museen/ (last visited 12.03.2023)

[28] Deutscher Bundestag

[29] Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Jersey (Channel Islands), Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Monaco, Netherlands, Norway,

Nonetheless, throughout the four surveys a positive trend was noticeable, showing that more institutions were working on their digitisation strategy. These results should be interpreted carefully since the participation of surveyed institutions dropped by 50% between the first and the last survey. However, where a strategy exists, it confirms that museums were focusing on the publication of the digitised collection (77%). Although there were certain institutions such as the Smithsonian, Washington D.C. (USA), which had already established a digital strategy in 2009, it appears that museums started to consider this idea around 2015 and are still currently in the process at the time of writing this thesis (Gries, 2016).
Since museums and cultural institutions do not seem to need a strategy to start to digitise their collections, which objects are affected by digitisation? The ENUMERATE Core survey mentions the broad range of cultural heritage collections. The types of digitised artefacts were as varied as the types of museums, with a slight dominance of two-dimensional objects, such as books, paintings, or photographs. Three-dimensional objects, such as sculpture or furniture, were much more present in museum collections than in other institutions, representing 84% of their analogue collection, against 33% in libraries and 47% in archives. Furthermore, the last survey conducted by the network of European museum organisations on digitisation, shows that Art and Design museums have already digitised 65% of their collection, whereas History and Archaeology museums only 27% and Natural History museums just 15% (NEMO, 2020). The authors of that survey are clearly pointing out the complexity of the digitisation of three-dimensional objects. The technical challenges of acquiring an object in three dimensions are mentioned later on in this work (see 4.1 p. 65), but this has also been stated by many experts in the field (Santos et al., 2017).
Concerning 3D digitisation, the project CultLab3D[30] from Fraunhofer should be mentioned. Since 2013, the project has developed several tools to enable 3D mass digitisation campaigns using 3D scanning (see for details on the technique 4.1.3.1 p. 70) and photogrammetry (see for details on the technique 4.1.3.2 p. 73). The process is computer controlled and completely automated (Tausch et al., 2020). Nevertheless, this pilot project is a pioneer in the field and far from being the standard.

Poland, Portugal, Rep. of Macedonia, Rep. of Moldavia, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, and United Kingdom.

[30] Competence Center Cultural Heritage Digitization, Fraunhofer Institute for Computer Graphics Research IGD, Darmstadt, Germany.

2.1.4 Forced closure, forced change

As can be expected, museums and cultural heritage institutions have been urged to change their policies due to the global health crisis and forced closures. According to a survey on the impact of the COVID-19 situation in Europe, 75% of museums have lost income. The big museums lose between 100,000 to 600,000 Euros every week. Consequently, 93% of museums have invested resources in the development of digital services to balance their financial loss (NEMO, 2021). However, the same report also states that no additional staff was hired (93% of museums) and that staff have instead been reallocated to 'digital' related tasks. It also appears that 81% of 'larger museums' have increased their digital activities, while only 47% of 'smaller museums' were able to do so. During this period, 80% of museums state that they are in need of assistance to conduct an efficient 'digital transformation'.

Getting an overview of the immense amount of projects related to digitisation and cultural heritage is almost impossible. In Germany, the database *Kulturerbe digital*[31] is collecting information on completed or on-going projects conducted in the country or in collaboration with a German institution. So far, the database has listed 2002 projects, of which just 40 used the key word 'restoration'[32], 16 'conservation'[33], and 17 'preservation'[34]. Based on this data, it can be concluded that only 2% of the listed projects dealt with restoration, 0.80% with conservation, and 0.85% with preservation. This information proves once again that the conservation field is not actively involved in digitisation.

Accordingly, we can say that there is no identifiable change of focus towards the integration of long-term preservation issues into digitisation initiatives at the moment.

2.2 The on-going preventive conservation debate

2.2.1 From fixed values to paradigm change

Fixed values appeared in preventive conservation in the 1970s, and were set at 50 or 55% ±5% for relative humidity and a temperature of 19 ±1°C in winter with a lower limit of 10°C, and 24 ±1°C in summer (Thomson, 1986, p. 268). But around 1990 a few experts from well-known institutes identified these climate requirements as stringent, which was a decisive turn for the field (Michalski, 2016). This evolution can be seen in the research strategy for preventive conservation at the Getty Conservation Institute (GCI), Los Angeles (USA).

[31] https://kulturerbe-digital.de/de/ (last visited 02.04.2021 and sadly not available anymore)
[32] Restaurierung
[33] Konservierung
[34] Bewahren

After focusing on environmental issues by setting up precise values for temperature and relative humidity during the 1980s, the GCI focused on communication between operative museum staff and directors in the 1990s. There the aim was to increase the awareness of preventive conservation issues and make clear, in order to become part of everyday practice, that this requires the commitment of the whole institution and not of just one person (Levin, 1992).

Tools from other disciplines were adapted to preventive conservation, understanding the implication of caring for museum collections. Some reference books were published such as *Managing conservation in museums*, in 1996 by Suzanne Keene and *Risk assessment for object conservation* in 1999 by Jonathan Ashley-Smith's (Keene, 2002) (Ashley-Smith, 1999). Additionally, risk assessment principles started to be systematically implemented in conservation in many museums all over the world (Waller, 2002).

Around the end of the 20th century, the fixed values for relative humidity and temperature were finally understood as being too restrictive and raising more problems than providing proper answers, in particular in the context of international loans. The French expert Gäel de Guichen advocated for a change of view on preventive conservation and not only being concerned with maintenance and climate monitoring. For de Guichen, preventive conservation is an *"essential part of a functioning museum"* and therefore should be part of the institution's overall strategy (de Guichen, 1999). According to the GCI, although risk management must be included in all museum management processes, this is still not the case (Dardes and Staniforth, 2015).

Despite the fact that the scientific literature on risk assessment and collection care management continues to flourish, for some specialists this is still not enough to solve the problem.

2.2.2 New approach

Robert Waller[35] had a different starting point. He has dedicated his work to risk assessment, including risk analysis for heritage collections, and has published many papers and gained his doctoral degree on the topic (Waller, 2003). Together with Stefan Michalski[36], Waller reflected on the reasoning model used in preventive conservation. They presented their thoughts at the ICOM-CC Triennial Meeting in The Hague (Waller and Michalski, 2005). According to Waller and Michalski, up to now preservation has been using a *"process-control"* model.

[35] former head of conservation at the Canadian Museum of Nature, in Ottawa, and current president of the Protect Heritage corporation.

[36] Former researcher at the Canadian Conservation Institute (CCI), Ottowa

The goal is to control each risk at an acceptable level, first through monitoring, then analysis and subsequently through making required adjustments. Sadly, very often the analysis and the subsequent adjustment are forgotten, and one ends up with habits, which Waller and Michalski call "*rituals*". The goal becomes the monitoring itself, when it should be a safer environment for the objects. Since so many risks threaten museum collections at the same time it can be overwhelming and difficult to take actions, which can lead to taking no decision. For that reason, Waller and Michalski advise a "*paradigm shift in preventive conservation*" from the "*process-control*" model towards a rationalized option: the "*predictive model*". The difference resides in the approach of looking at all threats together and not losing sight of the final goal. The point is to 'predict' and not to 'react' once bad things have already happened.

In order to do that professionals must understand the nature of the risk and the deterioration factors (see 1.2.2 p. 31), the object's material (raw and composite), as well as the associated conservation products. One assumed wrongly that fundamental science would have all the answers to solve the problem of preventive conservation (Michalski, 2016). But this argument can only be valid if the reliable data is gathered on the original objects in a 'real' context.
The same observation is made by David Erhardt[37] and his colleagues, listing the three steps of museum climate monitoring as follows and stating that step 1 is often forgotten:

> "1) Determine the effects of the environment on the materials and objects,
> 2) Set specifications based on the results of Step 1, taking into account the type of collection, the building and the local climate and economics,
> 3) Maintain and monitor the environment based on the results of Step 2." (Erhardt et al., 2007)

In the end, why do we spend large amounts of money restoring objects, and yet fail to ensure an appropriate storage conditions (Kissel, 1999).
Currently, the research focus in preventive conservation rests on damage assessment under experimental conditions in laboratories and should include in real-world contexts in museums as well. This is in line with the goal of spatial monitoring and the approach taken in this dissertation (see 1.1.3 Long-term preservation p. 27)

[37] Former Conservation Scientist at the Museum Conservation Institute of the Smithsonian, Washington D.C (USA)

2.2.3 Climate effects on objects

Since the goal is to be able to predict what happens on and to the objects, the effect of climate fluctuation needs to be monitored. At the moment too little work has been conducted on the effect of climate on museum objects which was the motivation of a few research projects such as *Climate4Wood* (van Duin, 2014). According to Paul van Duin[38] when the climate specifications are 52% ±3% relative humidity (RH) and 21°C ±2°C, and the situation in the gallery shows a variation in RH between 45% to 65%, the conservators need to know the effect on the wood panels (van Duin, 2012). He advocates for the need for 'real-life' data.

Kathleen Dardes[39] and Sarah Staniforth[40] appeal that we *"understand the collection material using scientific knowledge"* and for more empirical studies looking at damage due to climate fluctuations in the field, identified as a *"gap of knowledge"* (Dardes and Staniforth, 2015). It appears that there is still limited understanding involving the damage that may occur to some hygroscopic material in collections and that the degree of risk to hygroscopic material is not trivial to determine. Reconsidering the environmental guidelines has caused tensions amongst conservators and some people disagree categorically. More investigation into hygroscopic behaviour of materials under fluctuating relative humidity levels is therefore necessary to ensure that all objects can cope with relaxed environmental guidelines in museums. Dardes and Staniforth continued by advising conservators to expand their role and influence into further activities in museums, as this would benefit the museums environment and the collection care.

Although most studies have been conducted on easel paintings, polychromed sculpture, furniture, and historical wooden artefacts, it is confirmed that every object reacts in its own way. As summarized by Jo Kirby-Atkinson[41], the older the object is, the harder it is to make any general assumption and prediction (Kirby Atkinson, 2014).

It should be noted that very little work concerns archaeological wood. The hygro-mechanical study on the *Oseber*g ship in Oslo is one of the few researches conducted on archaeological oak (Dionisi-Vici et al., 2012).

[38] Head of Furniture Conservation at the Rijksmuseum in Amsterdam
[39] Head of Collections department, Getty Conservation Institute, Los Angeles (USA)
[40] President of the International Institute for Conservation of Historic and Artistic Works (IIC) and former National Trust Museums and Collections Director (UK)
[41] Former Senior Scientific Officer at the National Gallery in London (UK)

2.3 The road to sustainability

2.3.1 Green museum movement

As the problem of climate change and the impact of humans on the planet becomes increasingly important to societies all over the world, the question is also being discussed within cultural heritage institutions. Stringent requirements on temperature and relative humidity values in museums create a problem of high energy consumption, in particular in developing countries. However, museums often do not have much data on their energy consumptions (Staniforth, 2014).

By the early 2000s environmental sustainability became a topic for museum professionals and experts started to speak about how 'ideal' environment should be replaced by 'appropriate' environment and also advocated for a more localised approach. In 2008, the International Institute for Conservation[42] organized a round table in London on "Climate change and museum collections", involving all major research institutes in conservation and preventive conservation and established specialists (Saunders, 2008). The organisation of this workshop shows how topical the subject was.

In their book *"The Green Museum- a Primer on environmental practice"*, Sarah Brophy and Elizabeth Wylie clearly explain the movement (Brophy and Wylie, 2013). In 2007, while writing their book[43], Brophy and Wylie discovered that most Art and History museums did not feel the need to address environmental issues. They considered that since neither their collection nor their research focus were dealing with climate change, they didn't need to engage with the topic (Brophy and Wylie, 2013, p. 2). Brophy and Wylie pointed out that museums' responsibility in society is to educate and inspire change and they give three reasons for museums to become 'green': 1) as a mission for society; 2) to save money; 3) and as a positive impact on the global environment. Concerning sustainable collection care, some examples are given regarding museums reducing their heating and cooling costs by 50% after deciding to make a change (Brophy and Wylie, 2013, p. 6). According to Brophy and Wylie *"the planet is the ultimate housing for collections"* and integrating environmental sustainability into museum policy cannot be questioned.

Between 1990 and 2010 the Getty Conservation Institute (GCI) developed a large program to support museums in hot and humid regions all over the world in conducting research on alternatives to air-conditioning, using a combination of dehumidification, ventilation, and air circulation. Finally, the limitations of high-tech heating, ventilating and air-conditioning systems were understood, since their demands on resources, human as well as financial, were considered exorbitant.

[42] International Institute for Conservation of Historic and Artistic Works - IIC

[43] First Edition

Since 2010, the GCI has been working on the redefinition of how much resources should be invested in environmental control in museums (Dardes and Staniforth, 2015).
The other aspect is the construction of new buildings: museums or storage facilities. Over the last 20 years, the National Museum of Denmark has conducted a lot of research on low-energy buildings, advocating for more awareness and a commitment to stop building high energy consuming facilities for the storage of cultural heritage objects (Padfield et al., 2018). Normally, conservators are actively participating in new museum construction projects and work together with architects to reach a consensus and recommend specifications which are appropriate for the particular project. Unfortunately, their recommendations are sometimes excluded from the decision-making process. A list of five pieces of advice to conservation professionals are given by Perkins Arenstein and Schiamberg:

> "1) be a leader in preventive collections care projects; 2) learn who the project team members are and their areas of expertise so it is clear who is responsible for what; 3) respect the design team hierarchy and do not, intentionally or unintentionally, subvert the chain of command; 4) be an ally, not a critic; and 5) pick your battles wisely" (Perkins Arenstein and Schiamberg, 2014).

Here again, conservators can be useful assets in optimising collection storage, and potentially in reducing heating and cooling costs.

2.3.2 Sustainable conservation

Of course, environmental sustainability in museums is much more than just reducing the carbon footprint of the building, this also concerns resources: dealing with water supplies, choosing the appropriate building material, planning for future challenges (Cousins, 2016). As the NGO 'Sustainability in Conservation (SiC)', founded in 2016, advocates: the reduction of consumables in conservation laboratories is also part of the process[44]. In 2021, the sister initiative 'Ki Culture'[45] funded by the same person, Caitlin Southwick, published three guidelines to help professionals on the following topics: 1) Social Sustainability; 2) Energy; 3) Waste and Materials. These three publications prove the need for support and inspiration in the cultural heritage field.
In Canada, the 'Coalition of Museums for Climate Justice' aims to build *"museums' capacity to promote awareness, mitigation and resilience in the face of climate change"*.

[44]https://www.siconserve.org (last visit 12.03.2023)
[45]https://www.kiculture.org/ki-books/ (last visit 12.03.2023)

Useful resources are accessible through a database[46]. Additionally, the Association of Zoos and Aquariums provides their 'Green Practices' documentation among others on sustainability plans, policies and related budgets; energy; fuel for transportation; waste; and water[47].

On the level of policy makers, the 'European Green Deal'[48] defines priorities to make Europe climate neutral by 2050. The document was released in December 2019 and is strongly connected to the 'European Cultural Heritage Green paper'. Published in 2021, this document emphasises the idea that cultural heritage should be part of the solution, since culture and nature both have key impacts on society and the environment (Potts, 2021). Cultural heritage offers a platform for education and digital transformation, central challenges to solving issues linked to climate change.

A similar opinion is supported by the 'Climate Heritage Network' founded in 2019 after the Climate Heritage Mobilization Global Climate Action Summit held in San Francisco in 2018. For them climate change impacts people and their heritage worldwide and therefore, these two things cannot be separated and must be addressed together. Cultural heritage is *"a source of creativity and inspiration for action"* (Climate Heritage Network, 2019). On the other hand, looking into the past is a source of data about how people shaped their environment and delivers *"evidence of past adaptation"*. In their opinion the "*integrated nature-culture"* approach would mobilize specialists who were not yet involved (ie, archaeologists, curators, librarians, conservators), which in turn will aid in achieving sustainability goals. The link between ecological and social issues is believed will provide positive and constructive impulses towards the design of new solutions to mitigate climate change.

Since 2018 the International Council of Museums (ICOM) has a working group[49] dedicated to sustainability, mentioning the unique infrastructure that museums all over the world can offer to raise awareness on these topics. The 17^{th} Bodensee-Symposium, which is the conference of the ICOM German speaking countries will be held in June 2021 is focusing on "Museums and Sustainability"[50].

Now more than ever, museum professionals can participate actively to drive change.

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[46] https://docs.google.com/spreadsheets/d/1r6PFTN8zcNZqnN4N9DRmu49DT7EyTMt87ZUGat9eSm8/edit#gid=506344509 (last visit 12.03.2023)

[47] https://www.aza.org/resources-for-greening-business-practices#plans (last visit 12.03.2023)

[48] https://ec.europa.eu/commission/presscorner/detail/en/ip_19_6691 (last visit 12.03.2023)

[49] https://icom.museum/en/news/get-to-know-icom-wgs/ (last visit 12.03.2023)

[50] https://icom-deutschland.de/de/veranstaltung/267-17-internationales-bodensee-symposium-von-icom-oesterreich-icom-deutschland-und-icom-schweiz.html (last visit 12.03.2023)

2.4 Conservators in museums

2.4.1 Guardians of ethics

The conservators' role is defined in the professional guidelines of the European Confederation of Conservator-Restorer's Organisation (ECCO).

> "The conservator-restorer is a professional who has the training, knowledge, skills, experience and understanding to act with the aim of preserving cultural heritage for the future, and according to the considerations outlined below.
> The fundamental role of the conservator-restorer is the preservation of cultural heritage for the benefit of present and future generations. The conservator-restorer contributes to the perception, appreciation and understanding of cultural heritage in respect of its environmental context and its significance and physical properties."
> (European Confederation of Conservator-Restorers' Organisations, 2002)

Although the definition starts by legitimising the profession by mentioning that they are *"trained"* and *"skilled",* their role as 'caretaker' is clear. The responsibility that conservators bear on their shoulders is high. However, the main goal is to *"prevent decay"* and *"enhance"* the understanding of the original (ICOM-Committee for Conservation, 1984).
Ethical issues are addressed very early in the conservation-restoration education. All future professionals must understand the key role they will play in protecting cultural heritage. Many publications exist dealing with this topic. Ethical principles were established many decades ago, but their implementation and interpretation have varied over time and/or are continuously reassessed. The most actual discussion and overview on conservation-restoration ethics are published by the German Katrin Janis and the Spanish Salvador Muñoz Viñas (Janis, 2005) (Muñoz Viñas, 2004).
As Marie-Claude Berducou[51] pointed out during a meeting:

> "Professional ethics are formulated to frame a practice when exposed to potential threats: such as risk of corruption or technical breach. (...) Ethics are complex and have two roles : bound relationships within a profession to the inside, and give a positive and trustworthy image to the outside." [52]
>
> (Berducou, 2017)

[51] former Professor in Conservation of Archaeological Objects at Pantheon-Sorbonne University in Paris

[52] *"une déontologie professionnelle s'élabore pour encadrer une pratique lorsque celle-ci est exposée à de possibles dérives : comme des risques de corruptions ou des abus techniques (...) La déontologie est complexe et possède deux rôles : souder les relations à l'intérieur de la profession, à l'externe donner une image positive et crédible d'elle-même" (translated by A. Colson)*

There are probably several reasons why conservators are straddling the question of 'ethics', but this sometimes leads to the impression that they are the only professionals in cultural heritage really interested in this subject.
In fact, according to the ICOM code of ethics all museum professionals have the same responsibility.

> "Preventive conservation is an important element of museum policy and collections care. It is an essential responsibility of members of the museum profession to create and maintain a protective environment for the collections in their care, whether in store, on display or in transit" *(ICOM, 2017, p. 15)*

Unfortunately, conservators often place themselves in the role of the 'police officer', who are condemning the reprehensible attitudes or behaviours of others. Opting for this role is not necessarily a good starting point for interdisciplinary work and can create unwanted tension.

2.4.2 Role in museums

Museums' role is to *"preserve, interpret and promote the natural and cultural inheritance of humanity"* (ICOM, 2017). Sometimes 'Research' is even added to the list, as recommended by UNESCO (UNESCO, 2016b). In Germany, the position paper or memorandum *"Museums: Between Quality and Relevance"* edited by Bernhard Graf[53] and Volker Rodekamp[54] mentions the following goals: *"collecting, preserving collections, researching, exhibiting"* [55], but also communicating, and digitising, as the museums issues and tasks (Graf and Rodekamp, 2012a).
Logically, conservators are actively participating in the 'preservation' of museum collections, but they are not the only ones involved, they take an active part in all aspects of museum tasks. Over the last decades, the importance of preventive conservation* has been emphasised, to the detriment of remedial conservation* and restoration*, placing the conservators rather in the position of a collection manager. The situation of conservators in German museums is very well depicted by Bodo Buczynski and his colleagues in the German memorandum (Buczynski et al., 2012). According to them, conservators spend less and less time 'restoring' objects.
In 2015, and for the first time in history, the annual survey of the German Institute for Museum Research focused on conservation-restoration (Institut für Museumsforschung, 2016).

[53] Former director of the Institute for Museum Research from the Staatlichen Museen zu Berlin – Preußischer Kulturbesitz (until 2019)
[54] Former director of Stadtgeschichtliches Museum Leipzig (1996-2019) and president of the German museum association (Deutscher Museumsbund) (2010-2014).
[55] „ Das Sammeln, Bewahren, Forschen, Ausstellen „ – Translated by A. Colson

Of the 5,351 institutes participating to the survey that year only 72% of them took part in the conservation questionnaire. Very interestingly, many museums stated they did not conduct any conservation activities (30.9%) or did not have any need (18.1%), while 19.4% regularly carried out conservation and 19.2% occasionally. The other interesting fact is that only 18.1% of museums had a conservation department and 45.4% worked with freelancers. It appears that museums affiliated to public service, conducted more conservation activities, although they represent only 5.75% of the survey participants. On the other hand, local authorities and associations respectively representing 42.78% and 29.05% of survey participants, took part in the least in conservation activities. Generally, the survey showed a very clear link between the visitor numbers, which is also linked to the surrounding population, and the conservation activities. Basically, the more visitors, the more conservation activities were recorded. Other interesting elements were the kind of objects concerned to conservation activities. The most conserved groups were furniture and historical wooden objects (30.7%), technical objects (28%), paintings (25.1%). However, archaeological objects represent only 10% of all conservation activities.

2.4.3 Conservators' education

Here the point is not to give a complete overview of the education. But to point out the particularity of conservator training, which is multidisciplinarity.

In their professional guidelines on education, the ECCO[56] listed the fields that should be included in theoretical instruction:

- *Ethical principles of conservation-restoration*
- *Science (e.g., chemistry, physics, biology, mineralogy, colour theory)*
- *Humanities (e.g., history, palaeography, history of art, archaeology, ethnology, philosophy)*
- *History of materials and techniques, technology, and manufacturing processes*
- *Identification and study of deterioration processes*
- *Display and transport of cultural property*
- *Theory, methods and techniques of conservation, preventive conservation, and restoration*
- *Processes involved in making reproductions of objects*
- *Methods of documentation*
- *Methods of scientific research*
- *History of conservation-restoration*
- *Legal issues (e.g., professional statutes, cultural heritage law, insurance, business, and tax law)*
- *Management (collections, staff and resources)*
- *Health and Safety (including environmental issues)*
- *Communication skills (including information technology)*

(European Confederation of Conservator-Restorers' Organisations, 2004)

[56] European Confederation of Conservator-Restorers' Organisations

It appears that it is not a trivial matter to train future conservators in such a wide range of varied specialities. Several professionals already draw attention to the development of conservation into an academic field, alerting to the risks involved in developing theoretical knowledge at the expense of manual skills. Ashley-Smith's article summarises the problem very precisely, connecting this to the large societal shift of interest into craft-related practices which decreases over time (Ashley-Smith, 2016).

Lifelong learning is important in every field; however, it is absolutely crucial in conservation-restoration. Since conservators are very often in the position of coordinating and planning large projects, 'project management' modules could be integrated into the curriculum, a need that is becoming prevalent (Breitenfeldt, 2019). Bill W. Wei also suggests adding the concepts of material properties derived from material science, which conservators very often lack (Wei, 2014).

2.5 Summary chapter 2

All research takes place in a given 'ecosystem', which is the environment in which it is conducted. In order to depict this environment, a general background of the current situation in museums was necessary.

Museums entered the digital era a long time ago, but the transformation has proved to be more challenging than expected. With limited operating budgets, dedicating additional resources to operate a digital transformation is complicated. Collection digitisation is one aspect of this digital change, which is not always planned strategically. Yet most of the time the goal remains the same: gain visibility outside the museum doors in order to attract both scholars as well as visitors. Primarily two-dimensional objects are being digitised, and Art and Design museums have the highest numbers of digital collections compared to other types of museums. In the context of the global pandemic started in 2020, this trend was confirmed while digital activities had to be increased. However, conservation or restoration is very rarely associated with digitisation projects and conservators are hardly ever actively involved.

After spending decades defining strict values in preventive conservation the need to change paradigms has become inevitable. The focus is now on understanding the effects of temperature and relative humidity, as well as all deterioration agents, on the objects and consequently increasing analysis of 'real world' situations. The idea is to stop focusing simply on the tasks of monitoring but to try to understand what each individual object really needs.

In a changing world, where we are becoming more and more aware of the impact of humans on the planet, museums are also playing a central role.

The movement started slowly, but museums have understood that maintenance costs could be saved and that they should act as platforms to stimulate their communities to become more sustainable. Conservation laboratories are becoming more conscious of questions regarding the use of consumables, such as gloves, and other disposable resources.

Conservators often have a precarious position: either they are self-employed and waiting for museums to ask for their services, or they are part of the museum staff, which is rarely in a managerial position, which in turn means they have no leverage in the case of an important decisions regarding the collection. Even when consulted, their recommendations do not necessarily have the same impact as curators or other department leaders. The conservator's education is a melting pot of several disciplines, nevertheless certain aspects of applied engineering would be worth integrating into the curriculum, such as geodetic measuring and/or material science.

The following chapters should always be understood in light of this background, since the author is a conservator of archaeological objects.

3 AIMS AND DELIMITATION OF RESEARCH TOPIC

This chapter will pinpoint the research questions raised during the case study of the *Bremen Cog* conducted by the author at the German Maritime Museum (DSM) in Bremerhaven from 2014 to 2015, in her capacity of conservator, and from 2016 to 2019, as a PhD Fellow[57].

While the ultimate goal was to design a new support system, the first step was to look at the ship closely over time and identify 'problematic' areas to build the support accordingly. The risk in avoiding this step was to end-up with a support made for a 'modern ship' that would be symmetric and would not take into account the challenges of a conserved wooden ship.

Starting from the trivial question 'How can we measure?', it continued into the integration of spatial monitoring into a preventive conservation mindset, a preservation process that takes place in a museum context.

3.1 Research questions

3.1.1 Geodetic measuring systems as an alternative for monitoring

A change of geometry indicates the object's alteration and therefore, in the case of archaeological ships, should be regularly checked and integrated into the monitoring programme. A combination of several factors leads to aging, and thus the object's deformation over time is one element attesting to an on-going or historical degradation process. To 'capture' these changes is challenging, not only due to the object's size (the *Bremen Cog* is about 24m in length), but also identifying a suitable method. For objects in the range of a maximum of 2m, conventional tools such as a measuring tape or a calliper could be enough, although very approximate. But in case of large-scale object, the structure is too complicated and conventional tools no longer adequate to acquire the geometry and its changes. The current museum context and the development of geodetic measuring systems over the last two decades have both forced workflows used by conservators in museums to be revised. Until now, documenting and monitoring geometry was carried out with conventional techniques, such as technical drawing and photographs, sometimes complemented by surveying techniques. Here the question of technical feasibility is central, as well as whether already existing technologies can be adapted. The current practices of spatial monitoring in engineering and of archaeological ships will be presented in detail in Chapter 4 STATE OF RESEARCH p. 65.

Research question 1: How could deformation be monitored on archaeological ships over time and how geodetic measuring systems are suitable for this purpose?

[57] research thesis to gain a doctoral degree

3.1.2 Spatial monitoring as part of preventive conservation?

Since museums are going through significant changes in terms of legitimacy as well as relevance for society, financial support is often critical (Graf and Rodekamp, 2012b). More than ever preventive measures play a key role in reducing larger costs induced by negligence, when objects are left to fall apart. The tragic fire at the National Museum of Rio, Brazil in September 2018 showed that a lack of museum maintenance can lead to a catastrophe and the loss of '20 million items' (Phillips, 2018). The shocking fire of Notre-Dame de Paris Cathedral in June 2019, proved how fast several tonnes of medieval oak can vanish in smoke (Herzberg, 2019).

In addition, the costs for conservation projects should be calculated precisely, moreover, in the case of archaeological ships and all aspects must be planned carefully. As an example, the conservation of the *Mary-Rose* ship in Portsmouth costed about 35 million GBP and building the new museum to host the ship another 27 million GBP (Hocker, 2018, p. 168). Under these circumstances, gathering more information to foresee deformation, and prove the necessity for an intervention and to accurately plan an adequate solution is crucial. Combined with other parameters already monitored in a standardized way such as temperature and relative humidity, spatial monitoring would provide an additional level of understanding considering the alteration of the object. This issue is detailed under 2.2 The on-going preventive conservation debate p. 41.

Research question 2: Could spatial monitoring be part of preventive conservation* measures, as climate monitoring already is?

3.1.3 Integrate geodetic measuring systems to conservator's workflow

As a matter of fact, there is much more than just the technical aspects and feasibility, when considering the adaptation for pre-existing methods into another field. Museums operate in a particular manner, and function with structures inherited over several decades, which are not necessarily up to date (see chapter 2 BACKGROUND p. 37). These institutions are reacting to novelty with a stunning amount of inertia and the digital transformation is yet to be overcome. The information technology (IT) departments in museums are usually dramatically understaffed, since they are often not considered a priority. The hardware situation is no more satisfying and digital storage capacities are constantly working on the edge. On top of this, the broad spectrum of a museum's responsibilities also requires a broader expertise from the staff, most of whom cannot be employed on a regular basis. A turnover of staff is a common practice, which means that very few permanent employees are responsible for maintaining the museum policy and standards as well as performing the everyday tasks.

Considering this development and the revolution museums are undergoing, geodetic measuring systems ought to be integrated on all levels before they can be considered fully functional. This leads to the subsequent question. Some recommendations are presented in Chapter 6 CONCLUSIONS p. 139.
Research question 3: What is needed in museums to allow conservators to integrate geodetic measuring systems into their workflow?

3.1.4 Sustainability of spatial monitoring in museum context?

In the context of climate change, museums must lead the change and reduce their carbon footprint, therefore reduce heating and air conditioning needs (Staniforth, 2014). Currently, the relevance of strict climate values, 50 ± 5% relative humidity (RH) and 20 or 21 ±2°C for temperature, are very debated (Kirby Atkinson, 2014) (see 2.3 The road to sustainability p. 45). Therefore, understanding the impact of temperature and relative humidity on the object is central (van Duin, 2014). Evidence is required to prove that being less stringent does not threaten the objects and could provide solid scientific basis for the debate. In the meantime, maintenance costs could be reduced, and less energy wasted unnecessarily. This way, resources would be used smarter and therefore more efficiently. Museum climate has been focusing a lot on setting up, maintaining and monitoring specifications, when the first goal was to look into the impact of the environment on the objects (Erhardt et al., 2007). Monitoring archaeological wooden ships precisely, as they are costs-intensive objects, would give a clear overview and could help museums to plan wisely. Spatial monitoring can be seen as a sustainable answer to reducing energy and money waste. Showing that tax money is invested properly means also security for public institutions. This issue is treated under 2.3 The road to sustainability p. 45.
Research question 4: Can we adjust standard climate values based on tangible facts?

3.2 Research aims

3.2.1 Investigate geodetic measuring systems to monitor archaeological wooden ships

Over the course of the last twenty years, geodetic measuring systems have increasingly been implemented on archaeological wooden ships. The aim of this research is to investigate how they are used in the context of spatial monitoring. Throughout different case studies, to research projects, and finally to publications the actual outline will be drawn in this thesis. Although the basis of any academic work is a literature review, it is also important to realise that this can never be completely neutral. Being conscious of the fact that our own specific issues usually define the way information is collected and organized.

As a matter of fact, it is not enough to collect information on other projects. Several aspects must be considered: the staff involved and their professional backgrounds (disciplines and education), equipment (hardware and software), 'one time' initiative versus long-term measures, and the overall costs.
An exhaustive overview of the relevant literature is required to comprehend the current state-of-the-art and state-of-technology of geodetic measuring systems used for spatial monitoring of archaeological ships; this will be presented in 4.3 Spatial monitoring of archaeological ships in museums p. 85.

3.2.2 Prove the relevance of spatial monitoring in preventive conservation

As mentioned by many authors, there is no use in collecting information without a strategy and vision of how to exploit it. Gathering data for future analyses should be thought through rigorously but monitoring certain parameters over a long time-period of time can simultaneously enable better understanding of certain issues and put them into a clearer perspective. Preventive conservation has been developed separately alongside material-based and object-based disciplines in conservation. The ICOM-CC working groups illustrate how the conservation field is structured, as in the many disciplines based on object type and material. Here the list of all working groups: glass and ceramics; graphic documents; leather and related materials; metals; modern materials and contemporary art; murals, stones and rock art; natural history collections; paintings; photographic materials; sculpture, polychromy and architectural decoration; textiles; wet organic and archaeological materials; wood, furniture and lacquer[58]; and yet in the meantime preventive conservation and all associated measures apply to all object types and materials, and specifications are made accordingly. The idea is to look at a whole collection and to find mitigation strategies in order to get away from the 'one object' specification approach. Finding effective strategies is the most important element for optimization in preventive conservation. Therefore, the discipline gathers professionals coming from all backgrounds and education.
Spatial monitoring concerns the object directly, but not its surroundings. As a consequence, it certainly stands between preventive and curative conservation. On the one hand, no action or treatment is taken on the object, and no particular action is being planned either. Nevertheless, the goal is to monitor deterioration phenomena over time, potentially indicating that further curative measures will be required in the future. Looking at the definition of preventive conservation, it is evident that spatial monitoring could be classified as a related measure, but this is not yet the case. More details about preventive conservation can be found in 2.2 The on-going preventive conservation debate p. 41.

[58] https://www.icom-cc.org/en/working-groups/list (last visit 12.03.2023)

Since change of shape and deformations are required to be analysed together with other parameters, such as temperature, relative humidity, or light exposure, it would be logical to integrate spatial monitoring into preventive conservation measures. This research also intends to prove the necessity and relevance of an integrated approach analysing all the parameters globally.

3.2.3 Embed geodetic measuring systems in conservation-restoration practice

Revising the fundamental ideas and values of conservation of cultural heritage and being open-minded to integrating new methodologies and techniques is vital. Geodetic measuring systems present a great potential in assisting conservators with their responsibilities and associated tasks in museums. The level of accuracy and the maturity of the technology gives scientific credibility to condition reports and can support arguments for taking certain measures or intervention on an object. However, implementing new techniques into a workflow has to be done with caution and rigour. The aim of this research is to investigate how geodetic measuring systems match with the ethical values of conservation on the one hand and to identify possible limitations on the other.
It can be observed that in European museums the role of conservators is currently confined mostly to preventive conservation. The pressure resulting from understaffed teams and low budgets without a clear perspective of improvement, leads either to frustration or resourcefulness. Looking at alternative ways, definitely implies innovative options. The key-idea is to make geodetic measuring systems part of the standard methods in the array of useful tools required in preventive conservation. These aspects will be elaborated in Chapter 6 CONCLUSIONS p. 139.

3.2.4 Build a connecting bridge between geodetic measuring systems and conservation

Interdisciplinarity, multidisciplinarity or even transdisciplinarity are common key words in innovative research funding applications. Involving people from different backgrounds to solve a problem is certainly a way to achieve high goals, design new techniques and/or create new methodologies. But only if all participants find a common ground.
Conservators have been working together with other scientists for more than a century, mostly chemists, biologists and physicists (Caple, 2011). But except for the management of cultural heritage sites, monuments and buildings, conservators have been working with engineers only very sporadically. In museums or cultural heritage institutions, it is rare to employ engineers on a permanent basis.

All civilizations have participated in the development of geodetic measuring systems, but the first documented sources exist from Greek Antiquity.
A few mathematicians are considered as the founders: Joseph-Louis de Lagrange (1736-1813), Joseph Fourier (1768-1830), and Carl Friedrich Gauss (1777-1855) (Vaníček and Krakiwsky, 1986).
The following milestones can be mentioned in the technical developments of geodetic measuring systems and help to understand the field. In the 1970's, the electronic tachymetry was invented, making it possible to measure with a single instrument and not with two theodolites as before. Global navigation Satellite Systems (GNSS) were invented in the 1970s and provide geo-spatial positioning, enabling receivers to get longitude, latitude and altitude using systems such as GPS in the United States or Galileo in the European Union. Around 2000, 3D laser scanners were acquiring millions of points in a very short time thanks to advanced computer processing capacity. Measuring using photographs (photogrammetry) is almost as old as photography itself. But the first mentions date from around the 1840-50's from the French engineer Aimé Laussedat[59] and the German civil engineer Albrecht Meydenbauer[60]. In photogrammetry a significant development step was the invention of the stereo measuring instrument during the First World War and the early 1930's. The analytical plotter invented in the 1970-1980's made the coordinated recording more effective. The automatic method 'bundle adjustment' made the orientation of the camera much easier to calculate (Kraus, 2007, p. 3-7). But it is the digital cameras available since the 1990's, which made photogrammetry so important (Luhmann et al., 2020, pp. 19–32).
Experts in 3D geodetic measuring systems should be consulted when aiming to measure or monitor a structure precisely. This is simply their profession.
The importance of connecting conservators and engineers in geodetic measuring systems will be dealt with in 6.2.2 Speak '3D measuring' p. 150.

3.3 Target audience

3.3.1 Conservators

This work was conducted with the mindset of a conservator (the author) dealing with everyday issues in a museum context and looking for tangible solutions in order to fulfil an assignment. Here, the author never aimed to replace a specialist, being neither an IT, nor an engineer, but through collaboration with experts from different fields she intended to enrich her point of view and discover new ways to solve problems. She strongly believes that methods developed for other purposes can be adapted fruitfully to conservation of cultural heritage.

[59] Aimé Laussedat: born in 1819 in Moulins and deceased 1907 in Paris
[60] Albrecht Meydenbauer born in 1834 in Tholey and deceased in 1921 in Godesberg

As much as theory is helping to structure thoughts and to constitute the starting point of research, conservators want and need to go beyond. One would agree to depict the conservation profession as practice oriented. In fact, the 'need' for a solution appears to be intrinsic to anyone dealing with practical problems and the foundation for problem solving (Taylor, 2018). In this context, it is not surprising that conservators aim for tangible solutions.

The urge for practical solutions is inherent to all conservators, but it can also be a source of tensions between conservators and other museum professionals. Considering the vastness of tasks assigned to conservators, which implies caring for museum collections, feeling overwhelmed is very common. Under these circumstances it is hard to be creative and look for new solutions, when the pressure and the urgency to solve everyday problems is so high. As Chris Caple describes, conservators are a combination of technicians, scientists, parents, nay-sayers, frustrated curators and artists (Caple, 2000, p. 184). Other authors define conservators as 'care takers' being highly protective for the collection or group of objects they are responsible for.

Certainly, the profession's stereotype holds a negative image and some refer to conservators as "*pedantic nay-sayers*" (Frost, 1994). Usually, conservators have a lower position in the museum's hierarchy and rarely get the final word. This means that they might be consulted, but their negative image plays against them. Counterparts will often not be willing to listen to their arguments and reasons, leading to a stand-off effect for the conservators within the institution. In his article, Murray Frost describes his *"foundation principles, the 4 C's: complexity, conflict, costs and compromise"* (Frost, 1994), in which the last aspect calls for the conservator's social skills.

Exploring new techniques and optimizing workflows in conservation is definitely part of a bigger picture: how do conservators communicate and collaborate with other disciplines? Murray also points out the fact that most conservators do not have any mandate for research or the exploration of new techniques.

The purpose of this present work is to establish the benefit of including geodetic measuring systems for conservators included in everyday practice, as colleague to colleague. With the case study on the *Bremen Cog* (see Chapter 5 CASE STUDY p. 105), the theory is implemented into practice, and illustrates the feasibility and difficulties encountered in 'real life'.

As a matter of fact, every conservator is affected by the 'Cassandra syndrome'[61], and often foreseeing problems on museum objects is not well received.

[61] The Greek mythological figure Cassandra, King Priam's daughter, was condemned by Apollo to foresee the future and never be trusted. She suffered all her life that no one ever believed her, although she knew how tragic things would end (Schmidt, 1995).

Solid reasoning built on facts to advocate for preventive conservation, makes conservators' arguments trust-worthy and more likely to be listened to. This approach corresponds to the changes observed by Franck Hassard at the ICOM-CC meeting in New Delhi. He describes *"a paradigm shift from craftsman-based approach to scientific and research-based academic discipline"* (Hassard, 2008).
Spatial monitoring should be seen as an additional tool to encourage better communication between conservators and other stakeholders to help illustrating risks. Furthermore, as in climate monitoring, spatial monitoring is filling a gap between preventive and curative conservation, which is essential and useful for museum conservators.

3.3.2 Digital professionals in cultural heritage

Over the last two decades, architects, archaeologists, as well as other cultural heritage professionals have engaged in using geodetic measuring systems for cultural heritage. For logical reasons of size, architects or practitioners involved in the protection of cultural heritage buildings and sites were the first ones to get to use these technologies. This indicates that certain experience and knowledge already exists in using these instruments for other purposes than the industrial one they were designed for.
As part of this doctoral thesis several papers were reviewed from the scientific literature. The current situation on guidelines or standards and the use of 3D measuring systems within the cultural heritage sector was questioned. In this matter, knowing about museums infrastructure in information technology is important. This thesis offers an insider's view on the current situation in public institutions in Europe (see 2 BACKGROUND p. 37).
Additionally, primary questions of digitisation in museums concerns all the disciplines involved and a reflection on the different practices is needed. Very often conservators, who have never been confronted with a digital surrogate think that 3D data is 'all the same' and that one can achieve several goals with one data set. As a matter of fact, different goals can be reached simultaneously within a digitisation process, however the task and the data recording should be carefully planned and well examined.

Making other actors involved in the museum's digitisation process aware of conservators' needs advocates for more discussion and exchange between the disciplines. As a consequence, objects might be digitised just once, and still serve the needs of many, e.g., archivists, art historians or conservators.

3.3.3 Decision and policy makers

The editors Alison Bracker and Alison Richmond define what decision makers are in the cultural heritage field:

> "Those wo act in the name of conservation do things to irreplaceable works of art and design, archaeological artefacts, buildings, monuments, ruins, and heritage sites on behalf of society." (Richmond and Bracker 2009, p XIV)

Nevertheless, decision makers are required to control the budget and the museum personnel at the management level. For different reasons, conservators are very rarely the ones making final decision, setting up goals and budgets, or managing projects (Staniforth, 2014). As described in 3.3.1 conservators predominantly carry a negative image. Not willing to find consensus and worrying constantly turns out to be counterproductive, neither serving the interest of objects, collections or even the profession very well.

Preventive conservation* is, amongst other things, the art of finding a compromise between all stakeholders to preserve cultural heritage. Conservators must always aim for the option as close to an absolutely necessary minimum requirement for the preservation of objects and collections. Then again being capable of making compromises is mandatory to conduct projects in a healthy work atmosphere. Showing decision makers or museum administrators the relevance of the implementation of geodetic measuring systems for conservation as well as the potential of such techniques, will hopefully raise support to optimise existing infrastructures or even create new ones. According to the majority of legislations worldwide museum directors are responsible for all operations and need to make decisions, sometimes outside of their own expertise (Edson, 2004). The conservator's role is to prepare every 'dossier' in a sensitive manner and present all the results as clearly and understandably as possible, so that a decision can be made. Developing spatial monitoring and integrating this consciously into climate monitoring measures would support this approach and enable more dialogue.

Conservation is not a one-person job, but for everyone around the collection and the objects, as Susanne Keene likes to describe it. A lot of data is gathered; Even more so since the beginning of the digital era; Nevertheless little effort has been made to produce executive summaries of analyses and put them into forms for museum directors to incorporate into their decision-making process (Keene, 2002, p. 7).

3.3.4 Geodetic measuring engineers

Measuring the world accurately has always been a very important task, enabling trade and structuring society; from setting up calendars to standardizing lengths in order to build the Great Pyramids in Giza to a 0.05% accuracy (Bucher, 2012a). Although heritage buildings or museum artefacts are measured by geodetic measuring engineers during their studies and beyond, their knowledge about cultural heritage is limited. Nowadays, heritage science is a conglomerate of different disciplines, and understanding the ethics, goals and mind-set is central. For that reason, this research also addresses engineers using geodetic measuring systems to work on cultural heritage, either for a single project or on a regular basis. The point is to make them understand conservation ethics, and to integrate spatial monitoring to conservator's reasoning by putting these new aspects into perspective. Having the background to understand measuring techniques and the know-how to use them as designed are essential skills yet being aware of the conservator's agenda is absolutely required to open a pertinent discussion and enable collaboration.

Since interdisciplinarity is fundamental, communication between disciplines plays a key role. Mario Santana Quintero and Rand Eppich underline the importance of discussion in 'multidisciplinary' teams (Santana Quintero and Eppich, 2016). In an article published in the proceedings from the CIPA Symposium, Naif Haddad also mentions a lack of discussion between *"specialized technician and non-technician users"* (Haddad, 2007).

Under 6.2 Lessons learned p. 148, we will reflect on the collaboration between conservators and engineers.

Putting conservators' goals into context would be a tremendous help for project planning and the various discussions, which are part of this process. Speaking the same 'language' is a prerequisite to achieving common goals.

3.4 Summary chapter 3

The vital role of preventive conservation* in museums has reached a consensus over the last decades. However, the pressure on museum directors to cut budgets concerning maintenance and staff has indeed increased significantly in the past 20 years. The effect of strict climate values on the objects need to be monitored in order to justify or indeed relax them. This is the aim of this research, based on work conducted on the medieval ship *Bremen Cog*. But implementing any new methodology or technique into an existing system compels us to question current practices and existing infrastructures.

This work aims at investigating the current use of geodetic measuring systems implemented on archaeological ships; proving the relevance of spatial monitoring within preventive conservation measures; showing how geodetic measuring systems can be embedded into conservation-restoration practices, therefore serving ethical principles of the field; and reflecting on the essential need of communicating with the field of geodesy and conservation-restoration.

Primarily, this work is intended for conservators like the author, but also to any cultural heritage professionals, decisions makers and engineers willing to look beyond and into a multidisciplinary working environment.

4 STATE OF RESEARCH

This chapter presents fundamental notions necessary to understand how geometry can and should be captured. A few important elements must be taken into account, all coming from engineering, more specifically from geodetic measuring systems (see 4.1 Measuring and monitoring three dimensions: fundamentals).

Furthermore, the current practice on spatial monitoring in the conservation of moveable objects and the preservation of archaeological ships in museums is reviewed (see 4.2 Spatial monitoring in moveable cultural heritage and 4.3 Spatial monitoring of archaeological ships).

4.1 Measuring and monitoring three dimensions: fundamentals

4.1.1 Spatial monitoring - Principles

In engineering, spatial monitoring is part of a global approach in technical diagnostics called ‘structural health monitoring’. The objective is to monitor a structure* (object or building) and determine its ‘health’ (condition). The aim is to identify the damage, locate it, define its type(s) and severity (Czichos, 2013). Structural health monitoring is a long-term activity based on tracking changes of different natures over time.

Spatial monitoring follows this mindset, where, amongst others, the goal is to detect movements in time early enough to avoid and mitigate unexpected interventions. Like Andreas Eichhorn and his colleague describe: the reasoning behind the monitoring is to picture *“origin-effect-relationship”*[62] (Eichhorn et al., 2017).

In general, a monitoring system is designed to be performed periodically and can include several types of measurements* combined together to give an extensive understanding of the structure. Part of the measurement include geometry.

The ‘structural health monitoring’ methodology was originally developed to inspect bridges but was later extended to aircrafts, dikes, pipelines, sky scrapers, suspended roofs, towers, tunnels, wind turbines, as well as traffic installations (e.g. train platform), machine installations (e.g. crane track) and additionally for observing natural phenomena like landslides or embankments (Daum, 2013) (Eichhorn et al., 2017).

Bridges are considered as *“flagships of civil engineering”* and since any dysfunction would jeopardize public safety, a lot of care is invested in their long-lasting stability and maintenance (Wenzel, 2009, p. 1).

[62] “Ursache-Wirkungs-Beziehungen”

Monitoring geometrical changes is also very important in quality control in production lines in various industries: such automotive, machine, shipbuilding and aerospace (Luhmann et al., 2020, p. 15).
This preventive approach behind structural health monitoring has a lot in common with the one existing in the preservation of cultural heritage.

4.1.1.1 Typical workflow

As every project is unique, the approach is to design a singular solution for each object or structure* that needs to be investigated (Vaníček and Krakiwsky, 1986, pp. 175–190).
The design of a structural health monitoring system comprises six phases: 1) characterize the structure and set up the objectives; 2) identify and quantify the phenomena needing to be measured; 3) set up the coordinate system and select a measuring system, sensors and equipment, as well as appropriate targeting types; 4) validate the measurement system and visualization of the preliminary results; 5) set up the data management strategy and synchronize it with all datasets; 6) symptom analysis and diagnostics. The following diagram is inspired by the workflow proposed by Werner Daum, see Figure 4-1 (Daum, 2013).

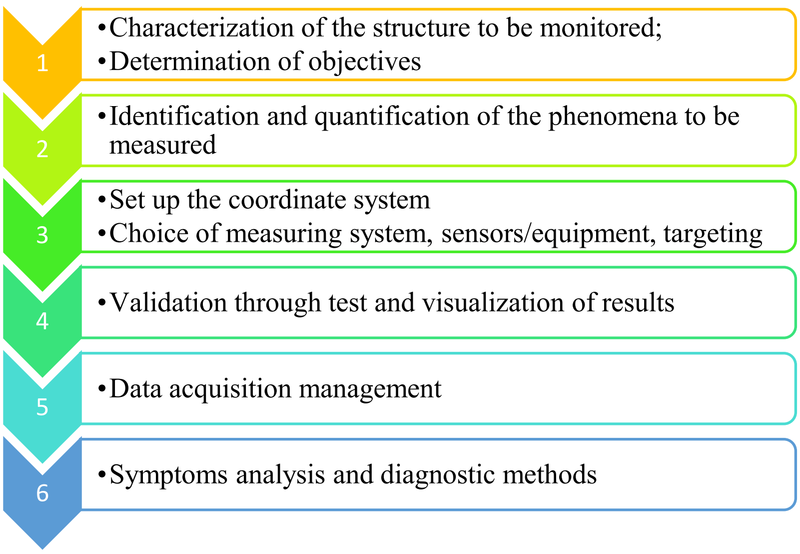

Figure 4-1: Generic design procedure for Structural Health Monitoring systems (after Daum, 2013 p. 416, adapted by A. Colson 2020)

During **phase one**, a review of all available information is made including all incidents, and modifications made to the structure in the past, this is also called collection of specifications. The motivation and expectation(s) behind the monitoring are stated as well. Additionally, all factors that might impact the measurement, called uncertainties*, have to be listed.

Phase two looks into all parameters involved in order to identify and quantify the phenomena needing to be observed. The necessary accuracy* is then defined, the phenomena and their nature are stated and located - where they are likely to occur on the structure*.

Phase three focuses on the necessary equipment and defines the installation specifications. The appropriate geodetic measuring system is selected together with the appropriate equipment and sensors, as well as the corresponding targeting* system.

During **phase four**, tests are conducted to validate the measuring system, calibrate* it and ensure the traceability* with international standards. It is of the utmost importance to check whether the designed system corresponds to the specifications collected in phase one.

Based on the monitoring expectations, the data management and processing are set up during **phase five**, which is crucial when many parameters are monitored simultaneously.

Phase six provides the final outcomes: recommendations and predictions, based on the symptoms* analysis and the technical diagnostic. The last phase is not trivial, since all types of geometrical changes must be separated and distinguished from each other and classified to understand the level of threat to the structure* (Eichhorn et al., 2017).

Without doubts, a careful planning of acquisition and monitoring is the key to success.

4.1.1.2 Mathematical description of movement

A movement is a change of position within a reference frame. Movement does not necessarily imply deformation*, which is a change of shape or size due to applied force or temperature variations. Motion takes place in three dimensions and is mathematically represented within a coordinate system xyz e.g.: 1) horizontal X-axis; 2) vertical Y-axis; and 3) Z-axis. Movement is always expressed in relation to the initial and the final positions.

Before describing the movements mathematically, it is essential to recognize whether the object is solid or not. Rigid body* is a notion used in physics to describe a solid object that does not deform or vibrate, using the assumption that deformation within the object is equivalent to zero and therefore can be neglected. A rigid body is considered to be interdependent, no internal distances between points can change. When a rigid body moves, its change of position is described as a transformation. Three kinds of transformation exist: 1) translations; 2) rotations and 3) change of scale (see Figure 4-2). Translation concerns a change in the coordinates (x, y, z) and rotation concerns a change in the angles $(\omega, \varphi, \kappa)$.

Since transformations can occur in three directions, three different translations and three different rotations can be established. In the case of a change of scale, it can increase or decrease (Luhmann et al., 2020, p. 57).

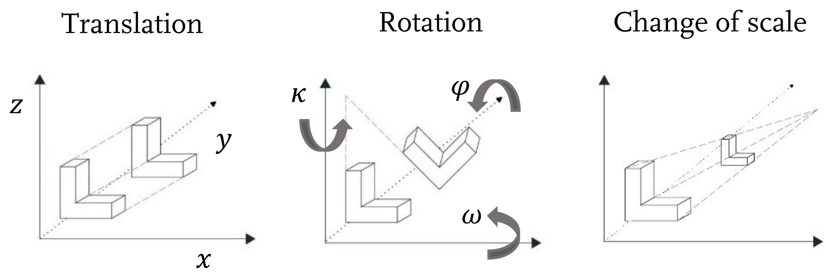

Figure 4-2 : Spatial similarity transformations (E. Cotrina-Meléndez 2020)

When a structure* is a 'non-rigid body', the transformations mentioned above apply as well as deformations. Andreas Eichhorn and his colleagues made a non-exhaustive list: *"shift, torsion, subsidence, elevation, drop, tilting, shearing, expansion, compression, bending, distortion, shearing angles, strain"*[63] (Eichhorn et al., 2017). A few possible deformations are depicted in Figure 4-3.

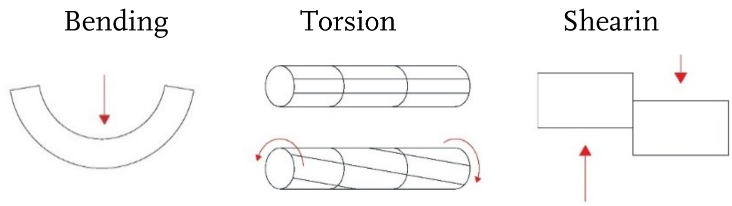

Figure 4-3: Deformations (E. Cotrina-Meléndez 2021)

4.1.2 Building a framework

4.1.2.1 Coordinate system

Taking measurements of the same structure repeatedly requires gathering geometrical information about the structure itself and its environment. The structure is then expected to move within the defined frame, which builds an invariant coordinate system. One way to see and understand if the structure moves, is to look at the relation between the structure points to the immovable points around it (Detreköi, 1988).

Two types of coordinate systems exist: 1) local: within the object or defined by the operator; 2) external: around the object. Both can be used simultaneously.

The coordinate system is also called the reference system. In the context of spatial monitoring of non-rigid bodies, it plays a very important role for every measurement.

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[63] *„Verschiebungen, Verdrehungen, Setzungen, Hebungen, Senkungen, Schiefstellungen, Scherungen, Dehnungen, Stauchungen, Biegungen, Verwindungen, Scherwinkel und Verzerrungen".* Translated from German by A. Colson

In practice, immovable points are installed around the structure* and permanently fixed. The coordinate system might be acquired with a different technique than the structure itself or using other sensors. The goal is to position and orientate the future data gathered on the object (Wieser et al., 2017).
Nowadays, Global Navigation Satellite Systems (GNSS) such as GPS[64] are used in most cases to establish a coordinate system outdoors. Indoors, a local coordinate system is required.
The use of a coordinate system is mandatory to simultaneously obtain a high accuracy* and precision* (see 4.1.4.2).

4.1.2.2 Targeting

Targeting is the action of marking one or several points in space through the installation of signs (Petrahn, 2019, p. 146). The aim is to measure always the same points and/or to automatize the data processing. It plays a major role in increasing the measurement accuracy*.
Three kinds of points can be marked as targets: 1) coordinate or reference points, used to orientate the object in space; 2) object points, the ones acquired on the object directly; 3) or border points, delimiting the area of interest.
Many different targets systems exist, here two will be mentioned: retro-reflective and coded targets. Retro-reflective targets have a surface which reflects the light (e.g. laser or flash light) back into its direction (see Figure 4-4a). Coded targets are used as a series, where every target is unique, working like a 'bar code' and helping to automatise the data processing (see Figure 4-4b).
Targets can be either fixed and stay over time between different acquisitions, called permanent targeting; or installed each time for one or several acquisitions, called intermediate targeting.
The reason behind the targeting is of mathematical and physical nature, linked to rigid-body motion (see 4.1.1.2). In the context of a spatial monitoring this means that the body of the structure will be represented by carefully characteristic objects points chosen in order to enable a statistical calculation (Detreköi, 1988) (see 4.1.4). The goal of targeting is to measure the same point every time, and with that examine the deformation*.

a b

Figure 4-4: Targets on the Bremen Cog – a) reflective b) coded (A. Colson 2021)

[64] Global Positioning System

4.1.3 Geodetic measuring systems applied in spatial monitoring

Although some monitoring systems focus on two dimensional changes, such as strain gauges[65], the acquisition of three dimensions prevails in spatial monitoring for large structures.

There are two ways to acquire geometric information: 1) measure single points (Total Station (TS)*, Laser Tracker*, Photogrammetry*); 2) or simultaneously collect a large amount of points in three dimensions, so-called point clouds (Terrestrial Laser Scanning (TLS)*, Photogrammetry*).

Currently, Total Station (TS)*, Terrestrial Laser Scanning (TLS)*, Laser Tracker*, Global navigation satellite system (GNSS)* are the most commonly used and considered as standards in spatial monitoring (Wieser et al., 2017) (Hennes, 2017). Along with the measuring systems mentionned above, photogrammetry* is also one of the preferred systems implemented in the context of spatial monitoring (Daum, 2013).

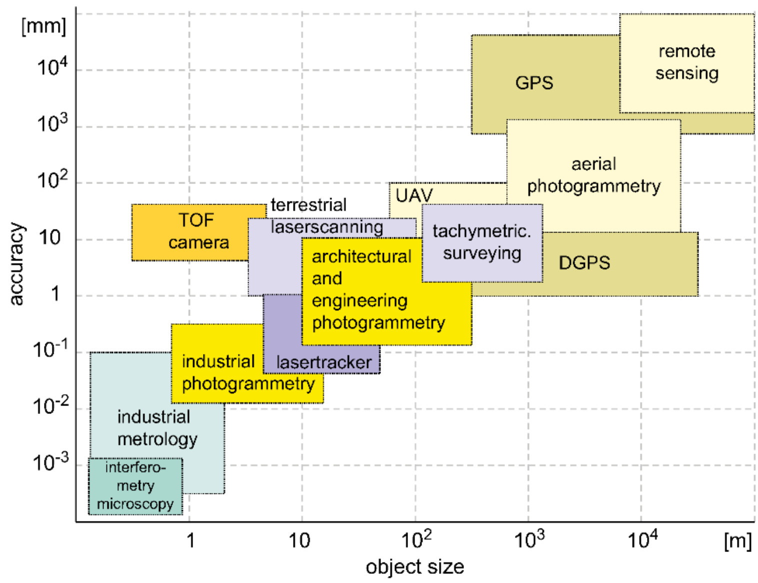

Figure 4-5: Relationship between measuring methods and object's size (Luhmann et al., 2020, p. 5)

Choosing the appropriate technology is always a compromise between available financial resources and the size of structure to be measured, see the relation between size and accuracy Figure 4-5. However, there is a simple rule: the more accurate the measurements need to be, the more expensive they become.

4.1.3.1 Laser based

- Total Station (TS)

A Total Station* is a portable device recording single points in 3D space by measuring horizontal and vertical angles and the slope distance using light (Bedford et al., 2016) (Howard, 2007).

[65] Strain gauge: a device for indicating the strain or forces of a material or structure at the point of attachment (Oxford online Dictionary; July 2020)

The electronic distance measurement (EDM) captures the received signals and determines the distance between the instrument and the target using infra-red light together with a reflective target or directly at the surface without any target (Deumlich and Staiger, 2002) (Chekole, 2014).

Figure 4-6 : Total Station at the DSM, Bremerhaven (M. Ditta 2015)

Since, in some cases, the device needs a geographical orientation, a Global Navigation Satellite System (GNSS) such as the Global Positioning System (GPS) is used to locate the instrument in space. Indoors a local reference system is set up (Petrahn, 2019), e.g. by total station or laser tracker measurements. The measuring range of the instrument goes up to 30m without reflector and to 250m with reflector. The typical accuracy is 1.5mm within 20m.

- Terrestrial laser scanner (TLS)

A laser scanner* is a measuring device that simultaneously acquires multiple points on a structure (Möser et al., 2012, p. 278).
As Pierre Grussenmeyer and his colleagues describe:

> "Laser scanning is an active, fast and automatic acquisition technique using laser light for measuring, without contact and in a dense regular pattern, 3D coordinates of points on surfaces" (Grussenmeyer et al., 2016)

A laser beam meets a high speed rotating mirror and is sent to several angles (Kraus, 2007, p. 419). Every laser scanner captures geometry without direct contact on the structure* and produces a three-dimensional representation also called a point cloud (Beraldin et al., 2010). The instrument will be moved to several positions to acquire the object's geometry. Point clouds collected from each position are also called 'scans' with some overlap between different positions (Kraus, 2007, p. 420).

Figure 4-7 : Terrestrial Laser Scanner performed by i3Mainz, DSM, Bremerhaven (S. Mehlig and C. Justus 2014)

Distance measurement is performed establishing on how much time the signal travels, based on transit estimation, also called ‘time-of-flight’ (TOF) (Beraldin et al., 2010). An extensive explanation of the mathematical and physical background can be found the scientific literature (Beraldin et al., 2010) (Grussenmeyer et al., 2016). An overview of the different scanning systems, including their respective accuracies and range, can be found as a table in the third edition of the publication on 3D laser scanning for cultural heritage from Historic England (Broardman and Bryan, 2018, p. 8). Although an adequate background is necessary to operate laser scanners, since scans are performed automatically, the instrument might be considered as ‘easy’ for non-expert users (Grussenmeyer et al., 2016).
The challenging aspects are to be found during the registration phase, which is the post-processing phase where all the scans are merged into a common coordinate system, once multiple stations have been recorded (Wieser et al., 2017). The measuring range of the instrument goes up to 120m. The typical accuracy is 1mm within 20m.

- Laser tracker

A laser tracker* is a mobile optical measuring device used in the industry to measure angles and distances. It works on the same principles as a total station* (TS), the difference is the use of absolute interferometer distance measuring. The interferometer works with one laser beam, split into at least two beams[66], which makes the acquisition of the coordinates more accurate than other systems (Meiners-Hagen et al., 2011).

[66] Michelson interferometer by the American physicist Albert A. Michelson (1852-1931)

The reference beam is then superimposed with the others creating interfering signals that provide precise distance information. Measuring more than one axis simultaneously speeds up the measuring time (Möser et al., 2012, pp. 349–350). Thus, moving target points can be tracked in space.

Figure 4-8 : Laser Tracker in front of the Bremen Cog, DSM, Bremerhaven (A. Colson 2017)

The device acquires only 'targeted' points, which means that the system cannot operate without targets. Currently, this is the most precise system on the market to acquire distance (Möser et al., 2012, pp. 392–400).
The targets are mounted in steel spheres of a specific diameter and the reflector is placed inside in the absolute centre, called a Spherically Mounted Reflector (SMR) (see Figure 5-16 p. 131). The instrument can be placed in different positions to capture a large structure and will always get orientation through the designated targets (see Figure 4-8). The measuring range of the instrument goes up to 80m. The typical accuracy is 11μm within 20m.

4.1.3.2 Image based techniques

- Photogrammetry

The principle of photogrammetry* is to use photographs to deduce geometry. In fact, images contain geometric properties that can be extracted based on known parameters (e.g., focal length of the camera lens). Every photograph is a two-dimensional capture of a three-dimensional environment, where 'bundle of rays' contains the imaged points as well as the perspective centre (Luhmann et al., 2020, p. 9).

The photogrammetric process is described by Karl Kraus:

> "Photogrammetry allows one to reconstruct the position, orientation and size of objects from pictures (...) without physical contact." (Kraus, 2007, pp. 1–2)

The results may be: 1) coordinates of separate points; 2) maps or plans; 3) geometric models; 4) rectified photographs called orthophotos, or three-dimensional models (Kraus, 2007, p. 1).

The relationship between two and three dimensions is governed by a mathematical law called 'central projection' (Luhmann et al., 2020, p. 7). For every photograph, the camera receives through its sensor a large number of light rays, called a bundle or bundle of rays. The 3D object coordinates are determined using the intersection between two rays (stereo photogrammetry), or multiple rays (multi-image photogrammetry) on the same object point.

In order to mathematically deduce the object's geometry, it is necessary to know every parameter involved. The first step is to understand what happens inside the camera, also called 'interior orientation'. The main parameters are: 1) the principal distance c, also called the calibrated focal length; and 2) the principal point (PP), also called image coordinates x'_0 and y'_0. A calibration of the camera is necessary to gather a list of these parameters, as every camera is different: e.g., type of lenses, or distance and position between lens and sensor. The link between all these parameters can be visualised on the pinhole camera model Figure 4-9.

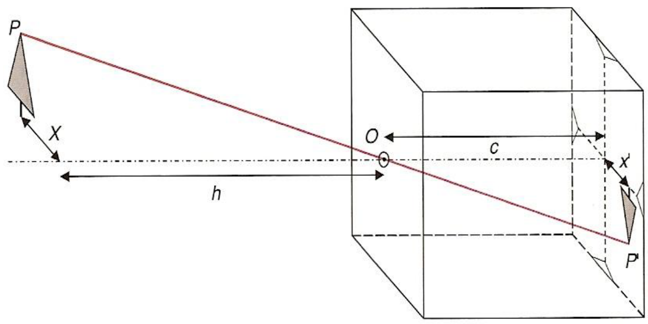

Figure 4-9: Pinhole camera model (Luhmann et al., 2020, p. 8)

The relationship between object and image is governed by the 'image scale', which is one of the main principles in photogrammetry, defined by the ground sample distance (GSD). Where m_B stands for image scale, h for distance between object point and perspective centre O, and the c principal distance (see Figure 4-9). This formula also specifies the ratio between a distance on the object X and the projected one on the image x'.

$$m_B = \frac{h}{c} = \frac{X}{x'}$$

The distance between object and camera, as well as the camera and its specifications can be chosen, which presents many more options than other measuring system.

For that reason, photogrammetry can be considered as more 'flexible' than other techniques. The appropriate settings are selected according to the defined objectives and the intended accuracy*.
The other crucial element is the position and orientation of the camera in space, which is the standing point from where the photographs are taken from. This is called the 'exterior orientation' (Luhmann et al., 2020, p. 9). Since the camera is in three dimensions, three coordinates define the position, and three angles define the orientation of all the bundles of rays (Kraus, 2007, p. 23). These six parameters are:

- Position X_0 , Y_0 , Z_0
- Orientation ω, φ, κ

In order to process the numerous images together, the 'bundles of rays' are fitted together in a process called the 'bundle adjustment' (see Figure 4-10) (Luhmann et al., 2020, p. 349-350). This triangulation method was developed in the 1950's and even today still plays a central role in the processing of images in photogrammetry (Luhmann et al., 2020, p. 25).

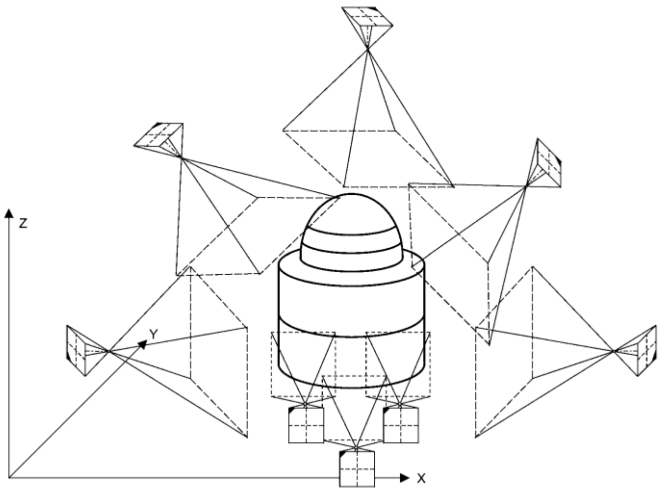

Figure 4-10: Example of a close-range image configuration (Luhmann et al., 2020 p. 352)

The accuracy of photogrammetry depends on the reliability of the points used to measure. Using natural features of an object, the accuracy is lower (0.5-2 px) than in the case of using targets (0.05-0.2 px). The measuring range goes up to 100m and the typical accuracy within 20m is 2.5mm and 0.125mm with targets.

- Structure-from-Motion

'Structure-from-Motion' (SfM)* is another type of image-based technique. It is based on the mathematical principles of photogrammetry but uses workflows from computer vision for the processing. It is also described as a 'strategy' rather than a separate technique. For this reason, it is important to differentiate between the two. The major difference is that natural image features are detected and matched fully automatic.

Some commercial software programs offer data processing workflow requiring much less expertise than photogrammetry, therefore making SfM a well-received technique among non-experts. The term 'Structure from Motion' comes from the fact that more images are needed to derive the geometry and that the sensor is 'moving' (Micheletti et al., 2015). After image orientation, dense point clouds, surface meshes or orthophotos can be generated.

Photogrammetry* is often referred to as 'traditional photogrammetry' or 'industrial photogrammetry'. Here the terms photogrammetry and SfM will be used to make a clear distinction between the two processes.

Photogrammetry* is considered to be a relevant alternative when the time dedicated to the acquisition is limited and/or the number of points is high (Luhmann et al., 2020, p. 726). It also offers certain advantages in comparison to other 3D measuring systems, as described by Jiang et al. The method is applied on bridges for being a non-destructive approach, requiring less personnel, the data acquisition being shorter, the possibility of reviewing the pictures again if needed, and useful feature of absolute repeatability of the measurements (Jiang et al., 2008). Although photogrammetry* has existed since the 19th century, its development took a massive turn with digital photography around the 1990's (Luhmann et al., 2020, p. 19) (Jiang et al., 2008) (see also 3.2.4 p.57). Its use in structural health monitoring has intensified since the 2000's on various structures* (Ye et al., 2016).

4.1.4 Processing and assessing data

4.1.4.1 Quality control

A few factors impact measurements and must be taken into account when designing a system for spatial monitoring, setting up the goals, analysing, and interpreting the results.

All measurements are compared to a reference, such as the length of a meter, following reliable standards. Since 1960, the International System of Units (SI)[67] precisely defines several measurement units and measurement parameters. Every measurement* uses the established units as a common language.

Making the perfect measurement is almost impossible, but it is central to understand why. Like Jay L. Bucher describes is his handbook on metrology:

> "When one makes a measurement, the measurement in some way is assumed to be wrong". (Bucher, 2012b).

[67] Système international d'unités (SI): modern form of the metric system – Based in Paris (*Le système international d'unités - The International System of Units (SI) -9th edition*, 2019)

According to Fritz Brunner[68] quality control of the equipment as well as the measurement, remains the most important part. He based everything on the following principle: *"how well something has been done"*. Being watchful at each step, is the way to *"transform subjective practical experiences into objective working method"* Brunner continues (Brunner, 2007). All elements must always be well studied, planned and documented.
To be able to ensure quality and reflect on it, everything must be transparent, and all impacting factors stated. This overview on reciprocal dependencies is called traceability*.
The list of all sources of error will determine the measurement's uncertainty* and the parameters that will be evaluated later on (see 4.1.4.2).

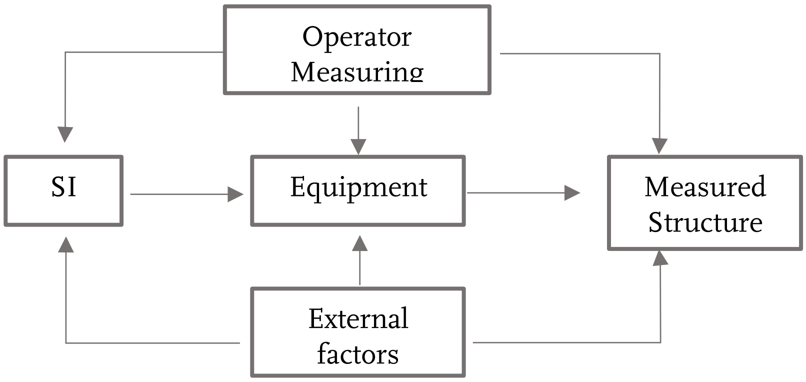

Figure 4-11: Impact factors for uncertainties (A. Colson 2021)

Errors can be systematic, for instance due to the equipment or the material measured, and they can be known and unknown. Random errors on the other hand are not predictable and therefore remain unknown. Systematic errors can be minimized through calibration*, maintaining a link between the standards (SI) and the measurement*. All factors influence each other as illustrated in Figure 4-11. The aim of 'quality control' is to establish how wrong the measurement is. The rule is always: *"one measurement is no measurement"*, implying that a measurement is never to be conducted just once.
The next aspect of quality control concern the measurement itself and notions such as: resolution, precision, accuracy and true value. The resolution* is the minimum distance between two points that can be achieved by the technique or the equipment.

[68] Professor Emeritus - Institute of Engineering Geodesy and Measurement Systems – Technical University of Graz (Austria)

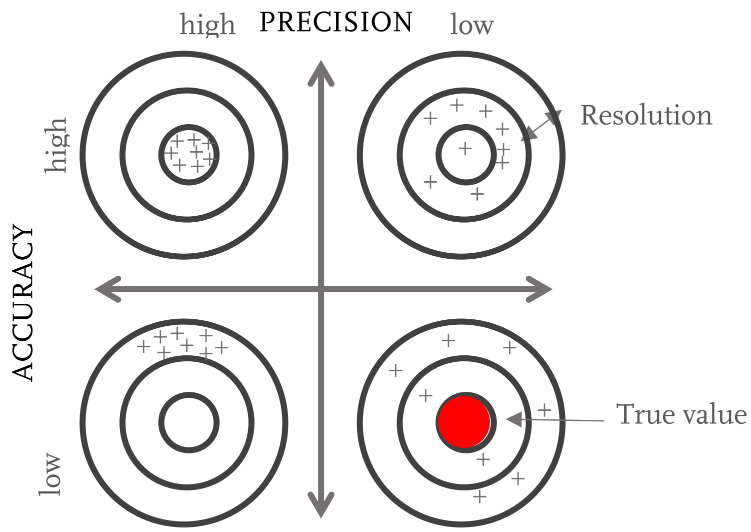

Figure 4-12: Accuracy vs. Precision (A. Colson 2021)

Precision* provides information on the reproducibility of the measurement, the noise and standard error (see 4.1.4.2 Evaluation).
Accuracy* shows how close the measurement is to the true value. The relationship between all the notions is illustrated in Figure 4-12. These four notions are essential to understand every measurement and their related reports.

4.1.4.2 Evaluation

As a matter of fact, the measured points or their measured position varies depending on several factors (see 4.1.4.1). The question is in which range? Naturally, the goal is to stay as close as possible to the true value and to reach high accuracy* and high precision* (see Figure 4-12). For that reason, every data set is evaluated to determine its degree of uncertainty*. Tests are conducted while planning the survey and alongside the acquisition of the structure to document the possible error(s) (Czichos et al., 2006, pp. 44–45). Statistics and probabilities are used to control, quantify and evaluate the data. It can also be described as the level of confidence towards the collected data and how it corresponds to the specifications defined by the recipient or the operator her/himself.
Various approaches exist to determine and evaluate uncertainty* (Czichos et al., 2006, p. 46). But the degree of uncertainty is often expressed by the standard deviation*, which is the combination of the true value, blunders[69], random and systematic errors (Heunecke et al., 2013, pp. 133–171).

[69] Careless mistakes

A measurement is rarely exactly the same all the time. The corresponding mathematical formula expresses the standard deviation (σ sigma), which illustrates the amount of variation of a set of statistical values or the dispersion of probabilities. Applied to geodetic measurement, it quantifies how the measured data spreads around the average:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{(n-1)}}$$

Where n = the number of samples in data set, x_i = the value of a given data point within the data set and $\bar{x}$ = the average or adjusted value of the data set. For spatial monitoring the σ value must be taken into account in order to guarantee the data reliability.

However, in practice the standard error(s) are reported and stated in the Root Mean Square* (RMS) or RMS-Error (RMSE) values instead of standard deviation (Luhmann et al., 2020, p. 104). The following equation defines the RMS for standard deviations in X, Y and Z.

$$RMS_X = \sqrt{\frac{1}{n}\sum_{i=1}^{n} s_{X_i}^2} \quad RMS_Y = \sqrt{\frac{1}{n}\sum_{i=1}^{n} s_{Y_i}^2} \quad RMS_Z = \sqrt{\frac{1}{n}\sum_{i=1}^{n} s_{Z_i}^2}$$

Signal-to-noise ratio* (SNR or S/N) is another parameter used to evaluate accuracy (Luhmann et al., 2020, p. 214) (Hastedt et al., 2019). The calculation can occur while planning the acquisition, the expected signal μ, divided by the noise here standard deviation σ.

$$SNR = \frac{\mu}{\sigma}$$

An alternative method for error propagation is given by the Monte Carlo simulation*. The aim is to simulate a large amount of measurement randomly generated through the algorithm and visualized histograms (see Figure 4-13) of error distribution usually depicting as parabola, more or less steep depending on the distribution (Luhmann et al., 2020, p. 654-656).

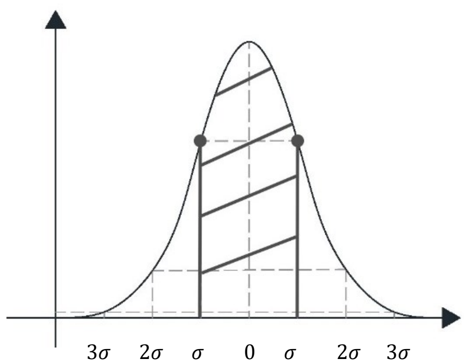

Figure 4-13: Histogram error Gaussian distribution (E. Cotrina-Meléndez - 2020)

4.1.4.3 Processing

All the 3D coordinates or images are usually being processed together. Since photogrammetry was chosen for the spatial monitoring of the case study (see 5 CASE STUDY p. 105) the focus here is on explaining the data processing and deliberately leave aside other systems.

Since every image holds random variables, every measurement is unique and contains its own error(s). In order to obtain consistent data, which means always the same result for the same measurement, mathematical adjustments are applied (Mikhail et al., 2001, p. 387).

Least square adjustment also called Gauss-Markov model, is the most common adjustment technique in geodetic data analyses. The most important example in photogrammetry is bundle adjustment*; also called triangulation or multi-image orientation. A spatial bundle of rays passes through the image coordinates and the corresponding perspective centre. During the optimisation process, reference points, object points, and image rays found on multiple images will be tied together, and inconsistent data (outliers) can then be sorted out.

The complete workflow is illustrated in Figure 4-14. The process occurs with the entire data set simultaneously, providing an optimum intersection of each point and with it an optimum position in space (Luhmann et al., 2020, pp. 349-352).

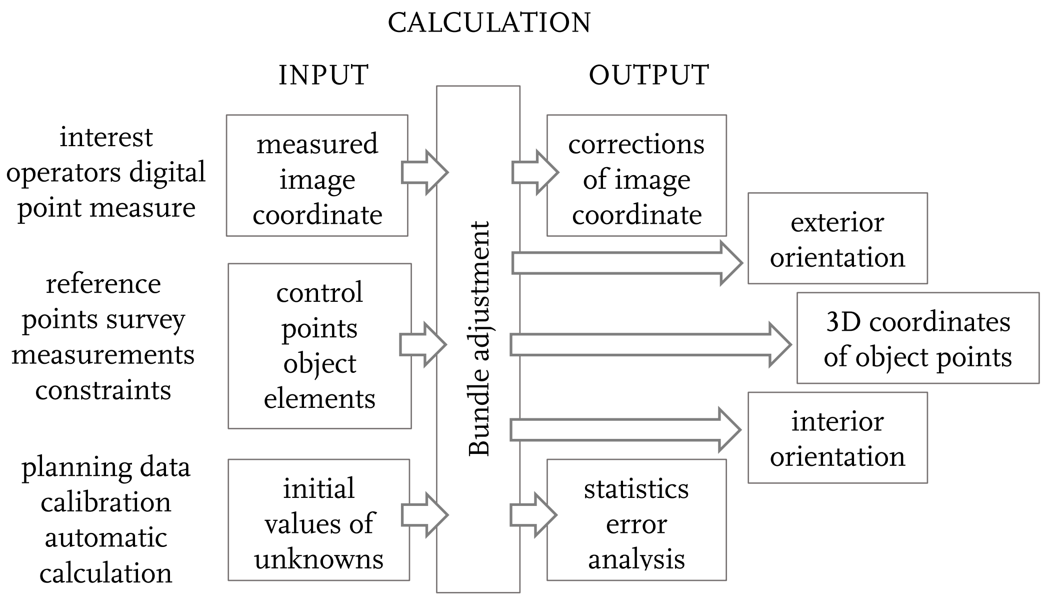

Figure 4-14: Data flow for bundle adjustment (Luhmann et al., 2020 p. 353)

4.1.4.4 Assessing

A few methods are used to make sense of the data before any interpretation. The next paragraphs aim at giving a short and basic description of these methods.

The three-dimensional similarity transformation determines translation, rotation, and optionally scale between two sets of points (epoch 01 - epoch 02).

The aim is to calculate the three rotations $(\omega, \varphi, \kappa)$, the three translations (X_0, Y_0, Z_0) and a possible change of scale (see 4.1.1.2 p. 67) (Kraus, 2007, p. 20). Where R stands for the orthogonal rotation matrix, and m for scaling factor, see the following formula:

$$X = X_0 + m \cdot R \cdot x$$

Congruence analysis (CON)* tests the coordinate system and how it is changing between two epochs, which is very important for spatial monitoring since it is the base for identifying statistically significant changes (Neumann and Kutterer, 2007). The idea is to check how robust the coordinate system is, thus between several epochs, to determine how it can be relied upon and to separate the inconsistent from consistent data (Neitzel, 2004).

The Fisher-Snedecor distribution, also called F-distribution*, is commonly used as probability theory to look into two variances. Additionally it can be combined with Student's distribution, also called T-distribution*, when the amount of data is large (Luhmann et al., 2020, p. 106).

Deformation* is a change of shape, where strain* is a part of this change, either expressed in percent or angles. Therefore, strain analysis is also a common method in spatial monitoring. Two kinds of strain exist: normal strain, which is either an elongation or a contraction; and shear strain, which is a change in angle (see Figure 4-3 p. 68). Several mathematical formulae are used to estimate strain*, but the two common ones are: Young's modulus and Poisson's ratio. Young's modulus is used to describe elongation and compression, to understand the elasticity of the solid. Poisson's ratio helps to measure the effect of deformation using the relation between the transverse and axial strain.

Using strain analyses to understand deformation enables one to step back from the global view, using the complete data set and look into local areas. The aim is to look into defined areas to understand the deformation phenomena (Alizadeh-Khameneh et al., 2018). Each measured point is connected to the two or three nearest points to build either a network of triangles or rectangles. This step helps to visualize the data using colours to see if the points moved between two epochs. The deformation or dilatation vectors can be visualized, and thus identify 'problematic' areas.

Finite-element-modelling* (FEM) is another method. Here, the principle is to assign known mechanical properties to each area or structural elements and see how different parts are reacting to each other. In other words, the geometry is 'filled' with defined properties. Since the computing of such physical problems is complex, the FEM numerical procedure makes an estimation faster and more efficient, looking only at the interactions. The model will then be subjected to forces and certain events such as a crash. FEM is used to make predictions in structural engineering for example planning supports or optimize a construction.

4.2 Spatial monitoring in moveable cultural heritage

After intensive search into the scientific literature only few examples of spatial monitoring were found applied to moveable cultural heritage and they will be shortly listed in this section. It shows that this approach is playing a role in long-term preservation on other objects than archaeological wooden ships.

4.2.1 Painting conservation

In the field of painting conservation, a few initiatives have been focusing on spatial monitoring.

In the Uffizi Museum, Florence (Italy), a three-dimensional acquisition of a painting on wooden panels: "The adoration of the Magi" by Leonardo da Vinci was performed (Guidi et al., 2004). The painting was surveyed using a structured light scanner[70]. After creating a 3D model, further analyses were conducted to get an understanding of the painting's depth. The authors state the potential of the applied methods to conservation for documentation as well as for monitoring, in particular to measure the impact of environmental variations on painting.

The National Research Council of Canada was involved in the laser scanning of the Mona Lisa by Leonardo da Vinci, exhibited in the Louvre Museum, Paris (France). The goal was not a spatial monitoring but a condition report as well as an analysis of the techniques used by da Vinci (Blais et al., 2007).

In 2009, Ingrid Hopfner used strain gauges and other sensors to measure mechanical structural changes for painted wooden panels at the Art Museum in Vienne (Austria) (Hopfner, 2015).

At the Conservation Department of the Art Academy[71] in Stuttgart (Germany), a series of projects have been initiated since 2011 to look at the surface of easel painting and the damages caused by transport at a microscopic level. The studies were financed by the German Research Foundation[72] and two doctoral studies in conservation were supervised by Professor Dr. Christoph Krekel and Professor Dr. Wolfgang Osten[73]. The aim was to replace subjective examination by an accurate method to evaluate the effects of vibrations due to transport (Hein, 2016, p. 3). Niclas Hein[74] used structured-light 3D scanning to compare geometrical changes before and after a major transport (Hein, 2016, p. 9).

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[70] Structured light scanner uses projected light patterns and a camera. The distorted lines enable to reconstruct the object three dimensionally.

[71] Konservierung und Restaurierung von Kulturgütern der Staatliche Akademie der Bildenden Künste (ABK)

[72] DFG-Deutsche Forschungsgemeinschaft; https://gepris.dfg.de/gepris/projekt/201547731?language=en (last visit 12.03.2023)

[73] University of Stuttgart, Institut für Technische Optik

[74] Painting conservator

The method was chosen for its accuracy in the micrometre range, where geometrical changes on paintings are usually observed (Hein, 2016, p. 62).
The first part of the project was completed in 2014. The follow-up project started in the autumn of 2016, conducted by another painting conservator, Carolin Heinemann, at the time of writing this thesis the project 3D-Artscan was completed in 2021[75], but the results only partially published (Krekel and Heinemann, 2020). Apart from these few projects, no other initiatives dealing with spatial monitoring of paintings have been found. It seems that 3D imaging systems are not broadly used on paintings to look at dimensional changes.

4.2.2 Tapestry conservation

One project in the field of historical tapestry and conservation has drawn particular attention. The project was conducted at the University of Southampton in partnership with the School of Culture and Creative Arts from Glasgow University. The focus was set on the identification of strain* on tapestries to support conservators in the evaluation of damages due to relative humidity variations (Bratasz et al., 2015) (Lennard et al., 2011). The strain* was measured with photogrammetry*, more precisely the principle of Digital Image Correlation (DIC) with two Charge-Coupled Device (CCD) cameras. Additionally, the point of strain* was obtained with a fibre sensor to verify the measurements obtained with DIC (Khennouf et al., 2010). The acquisition was conducted on historical and modern tapestries as a comparison, and the data was processed using the software DaVis. The Digital Image Correlation (DIC) technique reaches an accuracy of 0.1 pixels (Luhmann et al., 2020, pp. 609–613). The system is designed to be portable and movable, given that the equipment was located in the room for just the time of the acquisition. Temperature and relative humidity were also monitored during each acquisition. The strain monitoring was only conducted on one area of the tapestry and not on the entire artefact (Lennard and Dulieu-Barton, 2014). The results were visualized in colourful strain maps to help conservators make decisions on future mitigation strategies.
Thereafter, the project continued in Glasgow, conducted by Frances Lennard and Philipp Harrison as project leaders. At the time of writing this thesis, the second phase was still running and planned to end in 2021. Although the Digital Image Correlation (DIC) under the defined settings was providing promising results, further analyses revealed the complexity of monitoring a tapestry as a whole and challenges were pointed out, among others *"standard errors"* needed to be taken into account for any further analyses (Alsayednoor et al., 2019).

[75] http://www.abk-stuttgart.de/forschung/forschungs-projekte/konservierung-und-restaurierung-von-kulturgut/3d-artscan.html (last visit 12.03.2023)

Alsayednoor and his colleagues proved that their workflow was reliable, and that the finite element mesh makes analyses for spatial monitoring possible. For nearly ten years the Centre of Textile Conservation in Glasgow has been working on the topic and research is still ongoing.
Another project looked into the structural integrity of historical tapestries using near infrared spectroscopy (NIR), but no monitoring (Kissi et al., 2017). No other projects working with spatial monitoring of tapestry could be identify at this time, revealing the uniqueness of this research initiative.

4.2.3 Three-dimensional wooden objects

Some initiatives concerning three-dimensional wooden objects brought interesting insight on spatial monitoring.
The Westminster Retable furnishing the high altar of the abbey, London (UK), was monitored using photogrammetry* with an accuracy* of 20μm (Robson et al., 2004).
The experiment conducted on the altarpiece of the Santa Maria Maddalena's church in Rocca Pietore (Italy), showed that geometrical monitoring in the range of mm was possible. The use of laser sensors mounted directly on the altarpiece could reveal the relationship between relative humidity changes and dimensional changes of the wood. Unfortunately, the installation of such sensors is invasive and can only be done in very specific cases. Nevertheless, the experiment proved that tensions could be seen on the wood surface, provoking cracks and paint loss over time. Heating the church during the winter period must be done in a much more conscious way in order to mitigate the risk for the artwork displayed inside (Bratasz and Kozłowski, 2005).
In Poland, a group of researchers developed a *"web-based decision-making tool"* to help museum professionals assess physical damages. Based on temperature and relative humidity data from the object's environment, the software translates into levels of risk of failure for the given object. The calculation of potential cracks is based on experiments conducted on furniture as well as studies on the propagation of cracks. The tool is available online free of charge and works like a weather forecast application. There is no guarantee that the prediction will come true, but it helps to adjust the temperature and the relative humidity to be able to lower the risks. Simulating potential failure and being able to adjust the parameters accordingly is a very much solution oriented (Kupczak et al., 2018).

4.3 Spatial monitoring of archaeological ships in museums

4.3.1 Ships in museums

4.3.1.1 Historical ships under spatial monitoring

At the time of writing this thesis, only two examples of historical ships[76] under spatial monitoring could be found: 1) *Ebe* Schooner-brig on display in Milan (Italy); 2) and fireboat *Alexander Grantham* on display in Hong-Kong (China).

In Italy, the *Ebe* schooner-brig, dating from 1921, has been on display at the National Museum of Science and Technology Leonardo da Vinci in Milan since 1964 (Invernizzi et al., 2010). The ship was cut into 90 pieces to be reassembled in the museum, where weakened wood elements were replaced by modern wood and connected with stainless steel elements still supporting the vessel from the inside. According to Marco Iezzi[77] and Claudia Porta[78], the reconstruction was not documented at the time[79].

The first issues occurred in the 1970's, where the structure was found unstable to host visitors on the ship's deck and visiting of the interior was banned completely for safety reasons (Iezzi and Porta, 2020). In spring 2007, the bowsprit mast moved putting tension in the jib's robe, which subsequently broke. The jib[80] came down in the exhibition calling for some measures. A cooperation between a few specialists was initiated: Marco Fioravanti[81] (University of Florence), Clara Bertoloni-Cestari[82] and Franca Ceresa[83] (Politecnico di Torino). Although some conservation state reports were archived at the museum no extensive documentation was available (Comollo, 2010, p. 10). For that reason, the first goals were to document the ship and to understand how severe the wood was damaged. The first surveying campaign was conducted by Ugo Comollo as part of his master's thesis (2007-2008). Drawings and all documentation collected since the construction, as well as surveys, were put together into 2D plans as topographical representations to understand the deformation's origin (Comollo, 2010). The survey was conducted with a Total Station Leica T723 used targetless, and the data was processed with GEOS 7.7. and AutoCAD 2007 (Comollo, 2010, p. 66).

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[76] A historical object has been consciously selected and preserved over time whereas an archaeological object has been discarded or lost and recovered during an excavation. Therefore, the distinction is made here between archaeological ships and historical ships.

[77] Curator Department of Transportation – National Museum of Science and Technology Leonardo da Vinci (Milan, Italy)

[78] Conservator – National Museum of Science and Technology Leonardo da Vinci (Milan, Italy)

[79] Personal communication with the author

[80] Triangle sail that sets ahead the foremast of a sailing vessel

[81] Associated Professor Wood Technology – Department of Management of Agro-Food and Forestry Systems of University of Florence (Italy)

[82] Associated Professor in Architectural Technology – Politecnico di Torino (Turin, Italy)

[83] Lecturer and Architect – Politecnico di Torino (Turin, Italy)

Further campaigns were conducted and finally stopped in 2010, since a clear trend of movements could be identified corresponding to the relative humidity fluctuations in the room (Iezzi and Porta, 2020). Additionally, the deformation occurring on the wooden sailing ship were assessed and analysed using Finite Element Modelling (FEM), however the museum staff was not involved (Invernizzi et al., 2012) (Invernizzi et al., 2010).

Since 2007, the fireboat *Alexander Grantham*, built in the 1950's and decommissioned in 2002, is on display at the Museum of History in Hong-Kong (China). The metal ship is exhibited outdoors and the conservators have chosen to apply the structural health monitoring approach (see section 4.1.1 Spatial monitoring p. 65) for the long-term preservation (Tse et al., 2010). Different sensors described as *"extensive instrumentation"* by Jonathan Tse, chief conservator, were installed on the ship as part of the monitoring effort which makes the system invasive. The monitoring is part of a long-term plan and is conducted permanently. The data management is planned alongside the monitoring system in a very efficient way.

4.3.1.2 Relevance of spatial monitoring

Finding well preserved ships in an archaeological context remains a rarity. For this reason, the preservation of each ship find has always been 'unique' and must be understood within its political context (see 1.1.2 Societal and political impact p. 26).

Spatial monitoring of ships and its relevance is embedded in the post-conservation assessment effort. The critical review of results subsequent to conservation treatment is one of the pillars of conservation ethics (see section 1.2.1 Conservation documentation p. 28). The comparison between the state before and after treatment is the key element, but beyond that point regular checks ought to be conducted on the artefacts. This last step; here called phase 5 – long-term preservation (see Figure 1-1 p. 27); is crucial for ship finds considering the pioneering aspects of the treatments, as well as the objects' size (see workflow described under 1.1.3 Long-term preservation p. 27).

Wood mechanical properties is a very complex matter. When each wood species is giving a general trend on the material behaviour, natural features such as knots, branches or fractures also have a severe impact on the wood quality. For that reason, every test is conducted on 'green wood' with 'straight grain', but even then, variations remain. This means that elasticity, strength and vibration properties, should be understood as trends and orientations, not as strictly valid in all case (Kretschmann, 2010). But when it comes to waterlogged archaeological wood the burial environment and the heterogeneous degradation states of each part of the object, add a level of complexity.

There are two ways to assess the state of a wooden ship: 1) look into the wood's state; and 2) monitor the geometrical changes. Wood health assessments are very common and must be conducted to fully understand a wooden object. The wood degradation state is, among others, established by searching for the presence of microorganisms threatening the wood cells under microscope. Sometimes additional strength tests also need to be conducted. However, all these studies require invasive sampling, which is not always an option for archaeological ships. Since each plank will have different behaviour, it is never possible to sample each and every part of the ship, the data is always incomplete. Additionally, chemical analyses give a full picture of every component that could affect the wood during the conservation and beyond, such as sulphur and iron content, which are known to be very harmful (Sandström et al., 2003).

Figure 4-15: Wood geometrical changes (A. Colson, 2022)

When the moisture content* (MC) in wood lowers down, shrinkage will occur in three dimensions, but mostly in the tangential direction (see Figure 4-15).
These geometrical changes are assessed using antishrinkage efficiency* (ASE). This method is used on green wood as a standard to evaluate the success of a treatment, but is not always applicable on archaeological wood because of its high level of degradation (Giachi et al., 2009). Again, the relevance of such results is discussable, since they are based on the comparison between the volume of a sample before and after treatment, and do not reflect on the heterogeneous nature of the material present in a complex object, as well as its different level of degradation, over the dimension of a whole ship. However, it is the only standard tool available at the time of writing this thesis.
In this context, spatial monitoring offers non-invasive and non-destructive ways to gather additional data on a ship's geometry and potential changes, such as deformation. The data resulting from these various studies must be analysed together to recommend tangible solutions aiming to optimize the long-term preservation of archaeological ships on display in museums. Therefore, spatial monitoring is not only helpful to understand what happened but is also beneficial i.e., for the planning of new support systems or more generally the optimization of the display situation.

It should be seen as an unprecedented scientific innovation for the field of conservation.

According to a survey conducted by Marine Crouzet[84] and Laure Meunier[85] in 2016, more than 80 archaeological ships or boats are on display in museums in Europe, alone 19 in Germany and 26 in France (Crouzet and Meunier, 2016) (see Appendix A Non-Exhaustive List of Shipwrecks in Museums p. 1). However, very few initiatives exist for spatial monitoring of archaeological ships (Colson, 2017).

After contacting several institutes in Europe and exchanging at international conferences on this topic between 2015-2019, it appears that only five archaeological ships are currently under spatial monitoring (as defined in section 1.2.3, p. 32): the warship *Vasa* in Sweden (see section 4.3.2, p. 88), the flagship of Henry VIII *Mary-Rose* in England (see section 4.3.3, p. 92), the Roman barge *Arles-Rhône 3* in France (see section 4.3.4, p. 96), the Viking ship *Oseberg* in Norway (see section 4.3.5, p. 100), and the medieval ship *Bremen Cog* in Germany (see Chapter 5, p. 105).

4.3.2 The warship *Vasa* (Sweden)

4.3.2.1 Short history

King Gustav II Adolph's (1594-1632) warship was launched in August 1628 and sank after less than two kilometres outside the harbour during her first voyage in Stockholm's bay (Hocker, 2018, p. 3). After the incident, the cannons were salvaged, but the location was forgotten. Court cases opened at the time to determine who was responsible for such a disaster and much has been written about the failure. Since the ship was commissioned by the King, a significant number of written sources are available concerning the construction as well as the following trial.

Searched for a long time, the warship *Vasa* was discovered again in 1956 by Anders Franzén. Considered as the best-preserved 17th century ship and a Swedish national treasure, the decision was taken to raise her from the mud, where she was standing almost straight (about 5° incline to the port side) in the brackish waters of Stockholm's Bay. On April 24, 1961, the warship *Vasa* was lifted in one piece and brought to the shipyard for conservation. An action on such a scale was unprecedented and the recovery, benefiting from international press coverage, fascinated the whole world (Hocker, 2018, p. 3). Subsequently, the ship was excavated for almost six months and released from the mud that had protected the wood from biological attacks for centuries (Hocker, 2018, pp. 25–30).

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[84] Conservator of archaeological objects, Arc Nucléart Laboratory, research fellow at the time
[85] Conservator of archaeological objects, permanent staff member Arc Nucléart Laboratory, Grenoble, France

The oak ship *Vasa* measures 61 m from the figurehead to the top stern, 11.5 m in width and is the *"largest archaeological object retrieved from the seabed"* (Hocker, 2018, p. 1).

Figure 4-16: Vasa Ship Museum, Stockholm

4.3.2.2 Conservation

At the time of the salvage, conservation of archaeological organic material had so far mainly been conducted on small objects, which gave this project the status of 'pioneer'. As for all waterlogged organic material, the aim was to replace water with a consolidant, that would remain in the wood cells once the water retreated and keep the object in shape (see 1.1.1 Waterlogged wood p. 25).

Originally 10 years were planned for, yet 27 years were required for the conservation (Hocker, 2018, p. 31). After successfully using polyethylene glycol* (PEG) 1500 and PEG 4000 from 1962 to 1971, the ship was sprayed with PEG 600, and the 45% PEG concentration in the wood was attained at the end of the treatment in January 1979 (Håfors, 2010, p. 65). The surface treatment started a few months later together with a slow-drying process: reducing relative humidity from 95% to 70% over 9 years. The ship was transported to her permanent facility in 1988 (Håfors, 2010, p. 92). The *Vasa* Ship Museum was inaugurated in 1990 and the final relative humidity requirements were set to 60-65%, see Figure 4-16. (Håfors, 2010, p. 94).

The museum is a tremendous success and since its opening the yearly visitors' number has never decreased reaching 1,3 million in 2016 and 1,5 million in 2017 (Nordström, 2017) ("Stockholm's Vasa Museum sails into top spot on most visited," 2018).

As in any new construction, time is needed until the building performs as originally planned and/or wished for. Temperature and relative humidity were monitored from the start, but the conservators realised within five years after the opening that the air conditioning system was not running as hoped (Håfors, 1997). As a matter of fact, the museum's popularity became an issue since the building had originally planned to host a maximum of 600,000 visitors a year (Hocker, 2018, p. 121) (Cabello-Briones, Cristina, 2011, p. 48). The equipment couldn't keep up as the number of visitors kept increasing. Considering the volume of air 75,000 m^3, controlling the climate of such a large exhibition space contributed to the challenging task (Hocker, 2018, p. 119). The climate system was revised and optimized in 2004 and 42 sensors were installed and now constantly monitor the climate situation (Hocker 2018, 123-124). The targeted environment is a range of 17-20°C for the temperature and 51-59% for the relative humidity.
Beyond the completion of the conservation and the museum opening, research continued on and around the *Vasa*. Since 2003, a series of research projects have been conducted to deal with various issues: 1) chemical aspects: wood acidification, the interaction of PEG* and iron, the biological activity in conjunction with moisture content, and the wood's behaviour; 2) chemical properties and their effects on mechanical properties; 3) design of a new support system (still on-going) (Hall-Roth and Malmberg, 2005) (McAuley et al., 2006).

4.3.2.3 Set up spatial monitoring

Throughout the 1990's, the first deformations* and irreversible damages on the timbers were noticed. The ship lays in a 'dry dock' situation, originally on nine stanchions or *"cradle-stanchions pairs"* made of steel (Hurtado Sierra and Muñoz Garcia, 2014). The stanchions were doubled in 1994-1995 and are still adjusted today with wooden wedges manually (Hocker, 2018, p. 130). Additional supports were also installed inside the ship to prevent the decks from more sagging in the middle of the vessel. Looking at the hull's movements over time appeared to be the next relevant step, since it was noticed that the wood was deforming unevenly. In the late 1990's, following up on ideas already discussed at the beginning of the project, a geodetic measuring system was designed (Jacobson, 2003) (Hocker, 2018, p. 133). Several methods were tested thanks to the collaboration with Milan Horemuž, PhD in Geodesy and associate professor at the Royal Institute of Technology[86]. The technical and engineering university of Stockholm provided the know-how and staff. At first group of students conducted the acquisitions as practical exercises part of the university program, which has helped to keep the costs very low.

[86] Kungliga Tekniska Högskolan (KTH), Stockholm, Sweden.

The geodetic measuring system was planned as follows by Horemuž: 330 target points on the ship and 60 inside embedded in a local coordinate system of 28 control points on the walls, 2,300 measurements (Horemuz, 2003).
Currently, a manually operated Leica TDA5005 Total Station* is used to acquire the data (van Dijk et al., 2016). The parameters of the set-up can be seen in Table 4-1[87].

Coordinate systems – Reference points	29
Location outside the ship	60
Location inside	20
Targets on the ship	350
Targets inside	50
Number of measurements	2,000

Table 4-1: Overview of the monitoring setting from the Vasa (A. Colson)

Every point on the hull is acquired at least twice from two different locations to insure the accuracy* (Jacobson, 2003) (Johansson and Karlsson, 2017, p. 10).
The first acquisition was conducted in October 2000 and since then resumed twice a year, avoiding the high touristic season (May-September). The acquisitions are taking place in March and in October.

4.3.2.4 Monitoring outputs

After 19 years of monitoring and about 38 acquisitions, the collected data has provided a relevant overview of the ship's geometrical changes. The precision* was not defined clearly in the form of average error, but according to Horemuž the monitoring system of the *Vasa* reaches between 0.1mm sometimes 0.2mm (Horemuz, 2003). The standard uncertainty* is evaluated as follows: 0.1 to 0.2mm for control points and 0.1 to 0.7mm for detail points (Horemuz, 2014).
The geodetic data is computed by a self-coded program on MATLAB[88], customized by Horemuž specifically for this purpose. The data can be visualized using the pre-defined datasets to compare one acquisition with another in sections and globally on the whole hull.
Each acquisition takes about 120 person-hours (van Dijk et al., 2016) or 10 days with two operators (Jacobson, 2016).
Extrapolating the displacement* or the deformation* from the collected data is not trivial, as van Dijk reminds, and the mathematical principles of strain* are essential for the data processing and analysing (for more explanation see 4.1.4.4 Assessing p. 80) (van Dijk et al., 2016).

[87] Depending on the publications the parameters are different, no official feedback from the museum on this issue, at the time of writing this thesis
[88] Multi-paradigm numerical computing environment and programming language

Based on the gathered data, the average movement has been established at a rate of 1 to 3mm a year and since 2010 1-1.5mm a year (Hall-Roth and Malmberg, 2005) (Jacobson, 2003). The collected information was useful to quantify the impact of inappropriate climate condition for the ship, which lead to the purchase of a new air conditioning system in 2004 (Cabello-Briones, Cristina, 2011, p. 49).

In 2011, the project "*Support Vasa*" was initiated, and the collected data was used in correlation with other information on wood properties within a digital model obtained through the finite-element-method* (FEM), helping to understand how the ship performs overtime (Olofsson and Gamstedt, 2016) (Hurtado Sierra and Muñoz Garcia, 2014). The data is integrated into a simulation software used in structural engineering called ANSYS, to conduct some virtual tests in order to simulate different options for the new support system.

Currently, the museum also works on a GIS database to structure all the data collected so far into one platform. Additionally, an image-based digital documentation and the associated 3D-model, are being made from the inside of the ship using SfM*.

Some sections of the ship are also subject to a photogrammetric survey conducted by David Hauer (University of Oslo, Museum of Cultural History) to correlate the data collected from the other monitoring already in place[89].

The spatial monitoring conducted on the *Vasa* has involved many experts and the cooperation with external partners proved to be essential. An overview of all the involved disciplines was extrapolated and put into a diagram (see Table 6-3: Expert overview p. 142).

4.3.3 The Flagship of Henry VIII *Mary-Rose* (England)

4.3.3.1 Short history

In 1545 after 34 years of service, *Mary Rose* the flagship of Henry VIII's fleet, King of England, sank during a battle against the French in the Solent, in the bay of Portsmouth, England (Jones, 2003, p. 1). Some artefacts were salvaged soon after the wreckage and later on in 1836 by John and Charles Dean (Rule, 1982, p. 42). But in the 1960's, she was re-discovered for the last time during a survey campaign searching for historical ships (Rule, 1982, p. 47) (Marsden, 2003, p. 33). Between 1971 and 1978, excavations were conducted by Alexander McKee and Margaret Rule and about 20,000 artefacts were brought to the surface (Jones, 2003, p. 32).

> "On the wet cold morning of 11 October 1982, with the right tidal conditions, the raising of the Mary Rose in her support cradle began" (Jones, 2003, p. 34)

[89] Personal communication with David Hauer

The Tudor's flagship was raised in the presence of his majesty the Prince Charles of Wales and reached a worldwide audience of over 60 million people (Marsden, 2003, p. 145). The *Mary Rose* was brought to the historic dockyard in Portsmouth, where she is still on display today.

The flagship is mostly made of oak wood (Jones, 2003, p. 57). The surviving keel is about 32 m long about 8 m wide, and 12 m high (Marsden, 2003, p. 93). See the ship on display in the new museum in Figure 4-17.

Figure 4-17: Mary Rose, Portsmouth, Great Britain (A. Colson 2019)

4.3.3.2 Conservation

The conservation started by spraying the ship with cold water (2-5°C) to clean it from its sediments and preserve it from bacterial threats (Piva, 2017, p. 45-46). More than ten years of research and tests were necessary before starting the conservation treatment (Jones, 2003, pp. 68–69). The treatment was conducted with the 'two steps' polyethylene glycol* (PEG) method following up on other experience in Europe on similar artefacts. The ship was sprayed with PEG 200 up to a concentration of 40% in a water solution, followed by a heated solution of PEG 2000 concentrated at 60% in a warm water solution. Some PEG 4000 was applied manually onto certain areas of the ship subsequent to the drying process, where cracks where opened.

Date	1982-1994	1994-2004	2004-2013	2013-2015	2015-ongoing
Phase	Cleaning	Conservation step 1 low molecular weight	Conservation step 2 high molecular weight	Drying step 1	Drying step 2
Treatment	Cold filtered water 2-5°C	PEG 200 40% in solution	PEG 2000 60 % in warm solution	Slow and controlled air drying with air flow	

Table 4-2 : Overview Conservation History Mary-Rose

In 2013, the spraying stopped, and the controlled drying phase started, based on the doctoral research conducted by Glenn McConnachie (McConnachie, 2005). Large tubes were installed on the different deck levels of the ship and air was blown in constantly at 18-20°C and 50-58% relative humidity for a period of two years to enable a homogenous airflow all around the hull (Schofield et al., 2016). In 2015, the ship was freed of all the air tubes and could finally be observed in the new museum room surrounded by a large selection of artefacts found on board. For an overview of almost 40 years of conservation see Table 4-2.

4.3.3.3 Set up spatial monitoring

When the drying process started, the importance of monitoring the ship had not been proven. Eleonora Piva, conservator of maritime archaeological objects, conducted some research and eventually her doctoral studies on the monitoring of the *Mary-Rose* from 2014-2017. The project combined several monitoring approaches: climate monitoring of the environment, moisture content monitoring of the timbers, and structural monitoring (Piva, 2017, pp. 50–54).
The structural monitoring, which can here be understood as spatial monitoring, included four approaches: 1) an automatized total station survey; 2) a manual survey with a laser distance meter; 3) a manual crack measuring survey; and 4) a laser scan of the whole ship.
The total station[90] survey acquires a total of 35 targets on the port side of ship, three times a day (08:00, 16:00 and 00:15), every day, which is still on-going. The data is collected in Leica's bespoke software, GeoMoS Monitor and within this it can be viewed for selected time periods. A code was written in Python, which automatically generates graphs for the movements of each target. The system has been installed in 2014 (Piva et al., 2018).

[90] TS15 I 5" R1000 Total Station

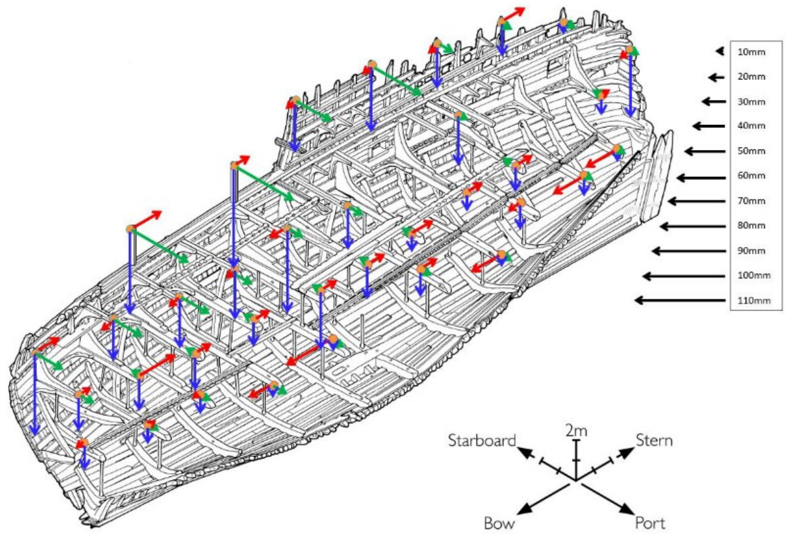

Figure 4-18: Port side map of the Mary Rose with all targets and their displacement in three directions (Piva 2017 p. 114)

The laser distance meter manual survey focuses on the starboard side in order to keep track of the distance between hull and cradle. A plastic shelf was built on each of the eleven locations on the cradle to be able to accommodate the laser pointer during the survey. The pointer was then placed manually to conduct the measurement bimonthly on a pin in the wooden timber and conducted from 2014 to 2017.

The crack survey consists of measuring the distance between two pins on the cracks. The selected locations were surveyed by hand with a tape measure, at first once a month and later bimonthly. The survey started with 477 locations and was later reduced to 100 areas of interest (Piva, 2017, pp. 80–81). Since 2016 these surveys are being conducted annually. Additionally, laser scanning has been undertaken of the hull at various intervals during the conservation. While spraying with PEG 200, PEG 2000 and at three different intervals during the drying process. These scans provide an overview of the movement of the hull overtime and the progress of the conservation treatment.

4.3.3.4 Monitoring outputs

The results from the structural monitoring conducted with the total station show geometrical changes up to 120mm (Piva, 2017, p. 110). The main tendency observed on all measured points shows that the ship was going downwards and that the higher decks tended to shift towards the port side see Figure 4-18 (Piva et al., 2018). Thanks to the acquired data some additional supports have been installed during the drying process, proving the relevance of the spatial monitoring as a preventive measure to be able to react fast and avoid further deformation.

The disadvantages of the method are the costs of the equipment and the set up as Piva describes and the need to install the targets on the original material, making it an *"invasive method not to be recommended"*.
The manual laser pointer survey was conducted easily by non-trained staff and almost *"cost-free"*. It was recommended to continue with this method and maybe to extend it to some further points on the ship. The cracks monitoring showed that 30% of the points were stable after a while, but the method is limited to providing information on the wood surface.
At the moment the data collected from the laser scanning surveys is being analysed as part of a PhD research project, which aims to understand overall movements.

4.3.4 The Roman barge *Arles Rhône 3* (France)

4.3.4.1 Short history

In 2004 a Roman barge dating from the 1st century A.D. was discovered in the river Rhône in Arles, about 90km North-West of Marseille, France (Long et al., 2009). After a number of archaeological surveys assessing the scientific significance of the shipwreck and considering the extraordinary good preservation state, it was decided to excavate the wreck extensively and raise the barge for archaeological study, conservation and ultimately for the permanent exhibition of Arles Museum as part of the European capital of culture year for Marseille-Provence 2013 (Marlier et al., 2017). The excavation was conducted over seven months from May to September 2011 under the supervision of the archaeologist from the Arles Museum of Antiquity[91] together with other contractors in archaeology[92], conservation[93] and commercial diving[94] (Marlier et al., 2017).
The ship was excavated underwater in the riverbed, completed section by section to avoid destruction by the Rhône's strong currents. Subsequently, each section was sawn and raised to be cleaned and documented on shore in a temporary shed. Although cutting the ship into ten sections was debated for obvious ethical reasons, the underwater conditions and the museum's opening schedule (2 years) were so constraining that this decision was justified.
Immediately after a careful cleaning was performed by conservators, each section was digitally documented using a coordinate measuring machine (CMM) referred as 'C-Track' produced by Creaform 3D (Marlier et al., 2017) (Ranchin-Dundas, 2012, p. 53).

[91] Musée Départemental Arles Antique (MDAA) - Sabrina Marlier and David Djaoui
[92] Ipso-Facto Mourad El Amouri and Sandra Greck
[93] Laboratories Arc Nucléart (Grenoble) and A-Corros (Arles)
[94] Benoît Poinard, from OCan

The data was imported into a CAD model in order to make a 3D models of each plank, furthermore a 3D reconstruction was later done by Pierre Poveda (Marlier, 2014, p. 55). The Arles-Rhône 3 is about 31m long and has a maximum width of about 3m. After extensive wood analyses it was determined that the majority of wood elements were made of fir tree and oak (Marlier, 2014, p. 173). A modern and accurate method of documenting the ship was defined since the beginning. During the excavation the timeline was to be followed and the wood had to go back into water as quickly as possible. The archaeologists effectively only had 48 hours to document every segment and the 3D measuring system offered the best option. The methodology was designed by Pierre Poveda[95]. Worksheets were produced including 2D drawings based on the 3D acquisitions, in order to support the conservators in documenting their work while cleaning the wood on the riverbank, before it was transported to Grenoble for conservation. See the boat in the museum in Arles in Figure 4-19.

4.3.4.2 Conservation

The conservation project of the *Arles-Rhône 3* started on the following premises: a fixed budget of 1,2 million euros and two years of time to achieve everything. Based on these terms Arc Nucléart, one of the biggest conservation laboratories in France for archaeological artefacts located in Grenoble (French Alps), designed a very tight schedule where nothing could be left aside or forgotten. Henri Bernard-Maugiron[96] and his colleagues took special care to think about every single detail and came up with a masterpiece of project management. Since very little time was available, the lab's infrastructure had to fit perfectly. The barge had to be cut underwater, and the size of each segment was chosen to fit the size of the conservation equipment, namely the freeze-dryer at Arc Nucléart. The conservation plan was also adapted and instead of using PEG 4000, standard procedure at the laboratory, it was decided to switch to PEG 2000 because of its quicker penetration into the wood (Bernard-Maugiron and De Viviès, 2014, p. 311).

Using reverse scheduling, it became clear that the freeze-drying step was to become a bottle neck and it was decided to use subcontractors from the start.

In order to reduce further issues post-conservation, it was decided to systematically remove iron nails (Bernard-Maugiron et al., 2016). The corrosion of archaeological iron in conjunction with a PEG treatment, more specifically the risk of sulphuric acid, is an as yet unsolved problem in the field of conservation. Only the iron parts from the bow, as part of the construction, were preserved. A PEG 2000 treatment up to 35% concentration was conducted over eight months, followed by the freeze-drying of five to eight weeks.

[95] Maritime archaeologist

[96] Conservator of archaeological objects

The other 11 elements were dried by a contractor. The support was made of steel to make it as light as possible, for a total weight of eight tons, designed and executed by a boiler making company in Grenoble.
The chosen presentation for the barge was the *"in use"* or *"as sailing"* position far from the in-situ situation underwater in the river Rhône. An extension of the museum was built to accommodate the boat and its artefacts, and a pit was designed to suggest a pier and the waterline, where the *Arles-Rhône 3* was placed (Bernard-Maugiron and De Viviès, 2014, p. 313).
In the end, a team of 22 people achieved the feat of conserving the Roman barge in such a short time, using 30 freeze-drying cycles and 300m^3 of 20% PEG solution.

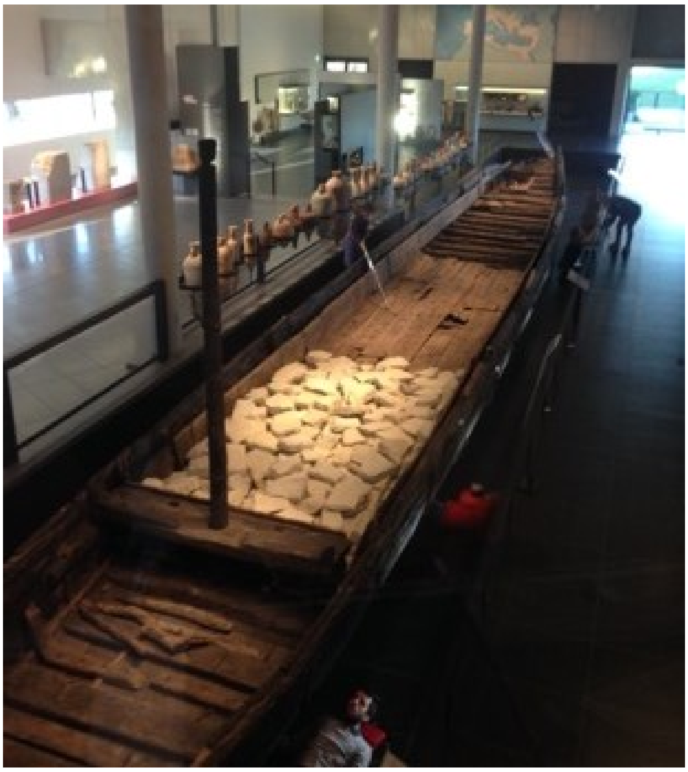

Figure 4-19: Roman barge Arles-Rhône 3, Arles, France (A. Colson 2017)

4.3.4.3 Set up spatial monitoring

In October 2013, the Arles Museum of Antiquity opened its doors to present the new centrepiece of the exhibition: the Roman barge *Arles-Rhône 3*. Very soon Marie-Laure Courboulès[97] alerted the board about the long-term preservation issue and the necessity of continuing to monitor the ship beyond the initial conservation treatment. She looked at potential threats to the ship and indicating factors to be monitored. The concept is based on three pillars: 1) risk assessment; 2) risk management and 3) the 3D monitoring.

[97] Conservator of archaeological mosaics at the museum

Risk assessment compiles all documents that have to do with the ship: from conservation reports to museum architectural plans and air conditioning equipment, as well as visitors' itinerary. Risk management on the other hand deals with the control and maintenance, i.e., visual control performed by the conservator, dusting the barge, retreatment of metal parts. Thirdly, the 3D monitoring was introduced later on, to enable all the contractors and staff involved to keep up with the amount of data produced, as well as linking everything together to conduct enquiry within the system. Daniela Peloso[98] joined the project in 2015 to assist Marie-Laure Courboulès in developing a database and a 3D monitoring system.

The 3D monitoring protocol uses a GIS database to link all the data together. All the information is georeferenced based on the topographical survey made during the excavation. A digital tablet helps the conservator to quickly visualize and helps to gain orientation. Additionally, an image-based acquisition is conducted using SfM* as a support for visualisation.

The climate monitoring is made through four sensors: one sensor about three meters high at a ten-meter distance from the boat; the other three along the ship on the pit's floor. The topographical survey is based on a coordinate system made of 11 control points installed in the room, acquired with a total station four times a year. On the barge itself 168 points are measured with a Total Station*. Some points are targets which are fixed on the metal support, some other under the ship. Until now no targets were glued or fixed to original surface of the boat. The data collected from the first acquisition made with the total station was then combined with the 3D models produced through SfM* (Courboulès et al., 2019). The survey is conducted three times a year and takes four hours with two operators. A maintenance contract is set up between the museum and Arc Nucléart Laboratory including a yearly visit. The research partnership with the Centre Camille Jullian[99] from Aix-Marseille University provides the support of Vincent Dumas[100] for the surveying and the equipment.

4.3.4.4 Monitoring outputs

The first ideas for the monitoring were already set in 2014 and developed into a GIS database, used on a tablet mainly during yearly maintenance visits.

The current spatial monitoring system can show some changes within the millimetres scale.

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[98] Archaeologist and 3D expert at Ipso Facto (private company)

[99] Centre Camille Jullian, Research Laboratory for History and Archaeology in the Mediterranean region and North Africa, from Protohistory to Antiquity. See https://ccj.cnrs.fr/spip.php?article2053 (last visit 12.03.2023)

[100] Archaeologist and surveyor, specialist in archaeological documentation and cartography.

The movements are rarely consistent, but a trend could be identified towards the ground signalling that the barge was sinking on its support. This tendency is stronger on the portside than on starboard, most probably a correlation with the *in-situ* position and the conservation treatments, but further analysis would be needed to establish a valid relationship. The data is not trivial to interpret, and the next step of the project would be to integrate the climate data into the analysis.

At this point, everyone involved agrees that the effort was worth it, and some further work is necessary. A few research cooperation and projects at a national and international level resulted from the original idea, showing that the issues are very innovative and do open new perspectives.

In the future, Marie-Laure Courboulès and Daniela Peloso hope to create a dedicated application, to facilitate data visualization and analysis. Measuring further impacting factors such as the wood acidity, examining changes of pH would add another level of understanding as well (Courboulès et al., 2019).

4.3.5 The Viking ship Oseberg (Norway)

4.3.5.1 Short history

The Viking ship Oseberg dates from AD 834 and was found in a burial mound close to Tønsberg on the farm of Lille Oseberg, about 100km south-west of Oslo, Norway. The wooden elements of the ship are mainly made of oak tree. Additionally, some components are made of beech and pine wood. The excavation was conducted by Gabriel Gustafson in 1904-1905 and it took three months to dismantle the ship. The burial mound was eroded, and the ship had collapsed under the weight of stones, preserving it in the sediment (Sjøvold, 1985, p 10). The archaeologists could clearly identify that the site had been looted, since the grave was disturbed. Nevertheless, two women with their jewellery, about ten horses, three sleighs and a large collection of artefacts were found on board. The wood carving quality of the ship and other decoration made this discovery a sensation.

The *Oseberg* ship is exhibited at the Viking ship museum as part of the Museum of Cultural History[101] (KHM) of the University of Oslo and located on the peninsula of Bygdøy. The building, designed by the architect Arnstein Rynning Arneberg (1882-1961), was built to accommodate three ships: *Oseberg*, *Tune* (discovered in 1867 and dated AD 910) and *Gokstad* (discovered in 1879 and dated AD 890), as well as some associated finds. Nowadays, the *Gokstad* ship is on the 100 Norwegian Kroner banknote testifying to the significance of the Viking ships in the modern state of Norway.

[101] Kulturhistorik museum (KHM), Universitetet i Oslo

The *Oseberg* ship is made of oak wood and measures 21.58 m in length, 5.10 m in width and 1.58 m in height (Sjøvold, 1985, p. 22). See the ships on display in the museum in Figure 4-20.

Figure 4-20: Oseberg ship - Museum of Cultural History Oslo, Norway (A. Colson 2017)

4.3.5.2 Conservation

The ship timbers were treated with linseed oil[102] and creosote[103] down to a depth of 2-3mm prior to the slow air drying (Braovac et al., 2011). It took nearly twenty years to reconstruct the ship and the wood was reshaped using steam (Bader et al., 2011). Almost 90% of the wooden parts still remain today and the damaged wood was substituted by modern wood treated in the same way to provide a homogenous aesthetic.

Between 2014 to 2020, the KHM was conducting a research project to find new conservation methods for the 're'treatment of the *Oseberg* artefacts, because these were conserved using alum[104], a product proven dangerous for archaeological wood. Although their work had nothing to do with the ship, the multidisciplinary team of chemists, conservators and archaeologists gave the impulse for the necessity to look after the three ships as well.

In the meantime, the new museum of the Viking era was being conceived and after considering several options it was decided to build an extension around the existing building. This would allow the assembly of all collections from the Viking era as well as the Viking ships (*Oseberg, Gokstad* and *Tune*) in the same building, as presently the rest of the collection is on display at the main museum building in Oslo city centre.

[102] Oil extracted of a flax plant
[103] Coal tar oil used as a preservative for wooden structure outdoor (Unger et al., 2001, p. 372)
[104] Aluminium potassium sulphate: conservation treatment used of archaeological wood (Unger et al., 2001, p. 372)

The new museum is planned to open to the public in 2026[105]. In conjunction with the new museum project, several assessments have been conducted on the three ships to estimate the wood condition precisely.
The *Oseberg* ship became part of a study focusing on structural monitoring conducted by David Hauer[106] and the topic of his doctoral thesis, at Oslo University (Hauer et al., 2022). The aim was to monitor structural response to seasonal climate variations, and deformations* due to creep* or cracks, to understand whether the movements were ongoing, as well as to explore the origin of the phenomenon.

4.3.5.3 Set up spatial monitoring

The spatial monitoring of the *Oseberg* ship includes several features: a standard climate monitoring, a load distribution monitoring, and the non-contact deformation monitoring. The project started in 2015. The museum's rooms are not climatised neither controlled, but temperature and relative humidity are monitored with several sensors inside and outside the building. The highest daily fluctuation is observed in summer during the high tourist season (Dionisi-Vici et al., 2012). This set up allows the conservators to have a full picture of the situation and enables data comparison gathered by the same type of sensors inside and outside.
The load distribution monitoring is a fixed system installed along the keel and on the existing metal support under the ship, made of 22 thin iron bars. A metal bracket is fixed on each bar horizontally, approx. 90°, and combined with two load cells resting on the floor on top of three feet. After lifting the entire ship once, the cells have been recording the change of mass distribution constantly. The load cells system includes a weighing module and compression cells produced in Sweden by the company Vetek[107].
Photogrammetry* is used for the spatial monitoring with object points glued to the ship, and on the support, additional reference points are installed on the ground. For the acquisition, coded targets are also placed on the ship, as well as crosses and scale bars building a frame to ensure a high accuracy*. For the *Oseberg* ship, 180 object points, measuring 5 and 8mm in diameter, were glued on the wood, fixed on flat metal washers with a reversible adhesive, to reduce the impact on the original material. A total of 1000 images are collected during each acquisition, taking seven hours with one operator. In order to facilitate the data processing and to maintain a high precision*, the ship was virtually divided into four sections. Each section would then be photographed as a separate dataset and fused together during post-processing.

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[105] https://www.vikingtidsmuseet.no/english/the-new-museum/ (last visit 12.03.2023)
[106] Conservator of cultural heritage
[107] https://www.vetek.com (last visit 12.03.2023)

Considering the limited space in the exhibition hall around the ship and the fact that the museum is open seven days a week all year long, the acquisitions were conducted at night to avoid visitors' traffic. The work was divided in to two evenings, instead of a full working day and conducted every fourth week (Hauer et al., 2022).

Camera flash is used to enhance the reflectivity of the object points or the coded targets. The data is processed using the Tritop software and system produced by GOM. The system was set up entirely by David Hauer with intermittent help of other specialists in the fields of geodesy, photogrammetry, 3D measuring.

4.3.5.4 Monitoring outputs

The monitoring output aims to combine the climate information, the geometrical data and the load distribution and put everything into account for the analysis. The current spatial monitoring system allows a detection of +/- 0.2mm deformation*. The decision to glue object points on the ship was taken very thoughtfully and different sizes were tested to comply with the monitoring aim and the overall aesthetics of the ship to the public. The staff from the collection department were consulted: archaeologist, conservators and the curator as well as the collection manager. One could argue that the system is not completely non-invasive since the targets are glued, but there is no loss of original material. A positive impact of this monitoring over the long-term and the information gathered herewith were prioritized.

The spatial monitoring system was first developed for the *Oseberg* ship, but now it is also implemented on the *Gokstad* and *Tune*. The same system is used for the spatial monitoring although reducing the number of targets to about 120 on the *Gokstad* ship. Likewise, a similar system is used to monitor load distribution.

The Museum of Cultural History of Oslo University has a 3D documentation department and some infrastructure, as well as the expertise existed within the museum before starting the spatial monitoring project. The relevance of using a 3D measuring system in a museum context was broadly understood and accepted among the museum decision makers.

The original 2D pictures are stored as JPEG, and load monitoring data as numbers in excel files, as well as climate information. Data storage is conducted according to guidelines for research data management at the University of Oslo.

4.4 Summary chapter 4

Planning and conducting a spatial monitoring project on archaeological ships in museums requires basic knowledge in geodetic measuring systems. Not only must the necessary mathematical notions be understood, even at a simple level, but also the corresponding used vocabulary (4.1.1. Spatial monitoring, p. 65). The importance of a coordinate system and targeting must be comprehended to define the objectives, knowing the impact that all specifications will have on the acquisition (4.1.2 Building a framework, p. 68). A few measuring systems are presented, the ones that have been used on the *Bremen Cog*, in order to understand their differences (4.1.3 Geodetic measuring systems applied in spatial monitoring, p. 70). Finally, the most common data processing and assessing procedures are summarized and presented as a non-exhaustive overview (4.1.4 Processing and assessing data, p. 76).

In moveable cultural heritage, a few initiatives concerning painting and tapestries (4.2 Spatial monitoring in moveable cultural heritage, p. 82) are reviewed.

The problematic of long-term preservation of archaeological ships in museums is not new, but at the time of writing this thesis only the listed initiatives actively looked into the geometrical changes of their ship(s) or boat(s) using geodetic measuring systems. In Sweden, the fully complete ship is presented in Stockholm: the warship *Vasa* is surveyed since 2000 using a total station (4.3.2 The warship *Vasa* (Sweden), p. 88). In Great Britain, the famous flagship of Henry VIII *Mary Rose*, is surveyed with an automatic total station several times a day (4.3.3 The Flagship of Henry VIII *Mary-Rose* (England), p. 92). In France, the roman-barge *Arles-Rhône 3* is monitored since its arrival in the museum after conservation in 2014, using a total station (4.3.4 The Roman barge Arles Rhône 3 (France), p. 96). In Norway, the mythical Viking ships, considered as national treasures, are monitored since a few years using photogrammetry (4.3.5 The Viking ship Oseberg (Norway), p. 100).

Although the international conservation community was contacted (ICOM-CC WOAM) no other spatial monitoring initiatives of archaeological ships was reported.

5 CASE STUDY

The spatial monitoring of the *Bremen Cog* is an original idea outlined by the author herself[108] following on from a discussion conducted during the workshop organised by the German Maritime Museum in Bremerhaven in November 2013. The experts pointed out the need for more data about the ship's condition in particular about the geometry for the design of a new support. After some preliminary research, the publications concerning the deformation monitoring of the *Vasa* were inspirational (see 4.3.2. The warship *Vasa* (Sweden) p. 88) and over spring of 2014, the idea of a survey on the *Bremen Cog* emerged. At the same time, the author's participation to the European Cost-Action "Colour and Space in Cultural Heritage" (COSCH) played a significant role to shape what became, in late 2015, a doctoral research project and the core of this thesis. The extraordinary well preserved medieval vessel will be presented in 5.1 The *Bremen Cog*, starting with a brief history and the motivation for the spatial monitoring. After that, the aims of the case study will be stated 5.2 Aims p. 118, followed by the work conducted before the beginning of the doctoral research, which can be considered as a pre-study 5.3 Preliminary trials – COSCH (2014-2016) p. 121. Finally, the case study is described in 5.4 Spatial monitoring 2016-2019 p. 128.

Figure 5-1: Discovery Bremen Cog October 1962 (Focke-Museum/DSM)

[108] The author was hired as object conservator and started her contract on November 1st, 2013. She was also present at the workshop on the future of the *Bremen Cog* and the new permanent exhibition.

5.1 The Bremen Cog

5.1.1 Short history

5.1.1.1 A sensational discovery

On October 8th, 1962, a large wooden vessel was discovered fortuitously in the river Weser close to Bremen (Germany). Building works were extending Bremen's harbour, located in the northern part of town, called 'European Harbour'[109], when the dredger operator saw a massive amount of wood appearing (see
Figure 5-1 and Figure 5-2).

Bremen, still called today the 'Free Hanseatic city'[110], has been an important economic trading point since the medieval period. The town hall and the market square, listed as UNESCO-World heritage sites[111], still show the city's prestigious past and its role in the expansion of the Hanseatic League during the 13-15th century. Merchants exchanged goods all over Europe using the river Weser to access the North Sea. However, in the late 19th and early 20th centuries, when Germany became a nation, this period of history was glorified and exploited for political reasons, making the Hanseatic League part of narrative and labelled 'proto' Germany (Belasus, 2017).

In 1962, when the harbour authorities were alerted to the discovery, Dr. Siegfried Fliedner[112] was the first expert on site and identified the ship as a medieval vessel. The shape fitted to the medieval iconography presented on wooden seals, still used today in many codes of arms[113] (Fliedner, 1985). The so-called 'Kogge' was described in the written sources as a large vessel made to transport goods, and in the popular imagination it was the ship that made possible the success of the Hanseatic merchants. Numerous written sources mention a large vessel called a '*KOGGE*', building up on the myths surrounding the Hanseatic League. The '*KOGGE'* or *'Cog'* in English, became an emblem of a successful tradership and pre-German engineering.

But until her discovery, there was absolutely no evidence ever found in an archaeological context, making the *Bremen Cog* an immediate *"sensation"* (Heinsius, 1982). The ship was the best preserved large medieval seafaring vessel found in North-West Europe. For this reason, the *Bremen Cog* continues to play a central role in maritime and ship archaeology today (Belasus, 2017).

[109] Europahafen
[110] Freie Hansestadt Bremen
[111] https://whc.unesco.org/en/list/1087/ (last visit 12.03.2023)
[112] Art Historian from the Focke-Museum in Bremen
[113] PhD Fellowship in Art History Helga Berendsen (German Maritime Museum, Bremerhaven)

5.1.1.2 Excavations

The wooden ship was laying on her starboard side and some elements of the port side were appearing at low tide (Fliedner, 1974). The river Weser is subject to tidal ranges and the fluctuating water level was damaging the ship, which was threatening to fall apart. Consequently, the decision was taken to dismantle her. The first excavation campaign was set up in Autumn 1962 under the supervision of Dr. Rose-Marie Pohl-Weber[114] and supported by divers. The visibility was very limited and only a few parts were recovered. The works had to stop in December with the first ice preventing any river traffic (Pohl-Weber, 1969).
The excavation continued in the same manner in summer 1963, and it was clear that the deeper the divers went in the wooden structure, the more challenging it became. It was almost impossible to distinguish wooden planks from each other and very complicated to carry out any delicate work (see Figure 5-2). For that reason, Pohl-Weber decided to work with a diving bell, enabling the work to continue directly on the ship in a 'dried' context. After finding both the right equipment and funding, the diving bell arrived on site in Summer 1965, and was available for one month. The team managed to study 274 positions on the riverbed, over 1400m^2, at an average of 11 positions a day, in order to collect all the remaining wooden parts and artefacts belonging to the *Bremen Cog* (Pohl-Weber, 1982). The timbers were stored in Bremen.

Figure 5-2: Rescue excavation in the river Weser, 1962 (Focke-Museum/DSM)

[114] Ethnologist at the Focke Museum in Bremen from 1965 to 1990. As the first woman in Bremen, she directed the museum from 1975 to her death in 1990.

5.1.1.3 Reconstruction

The ship timbers were stored in tanks in Bremen in a 1% Flurasil[115] water solution until the decision was made to establish the German Maritime Museum in Bremerhaven, where the *Bremen Cog* would be one of the central pieces of the permanent exhibition.

Already in 1966, Werner Lahn[116] was employed to coordinate the ship's reconstruction and together with Hans-Walter Hoheisel[117], he took care of the project planning. The Museum was under construction following the design of the famous German architect Hans Scharoun (1893-1972) and conducted by two Bremerhavener architects[118].

The dedicated building 'Cog Hall'[119], especially designed for the ship, was already standing when the tanks arrived by boat through the river in Bremerhaven. Scharoun drew a gigantic window front, comparable to a glass showcase, opening completely to the North-East and towards the old harbour, enabling passers-by to see the *Bremen Cog*. The transport of all timbers was completed in late summer 1973 and the reconstruction started soon after (Lahn, 1985).

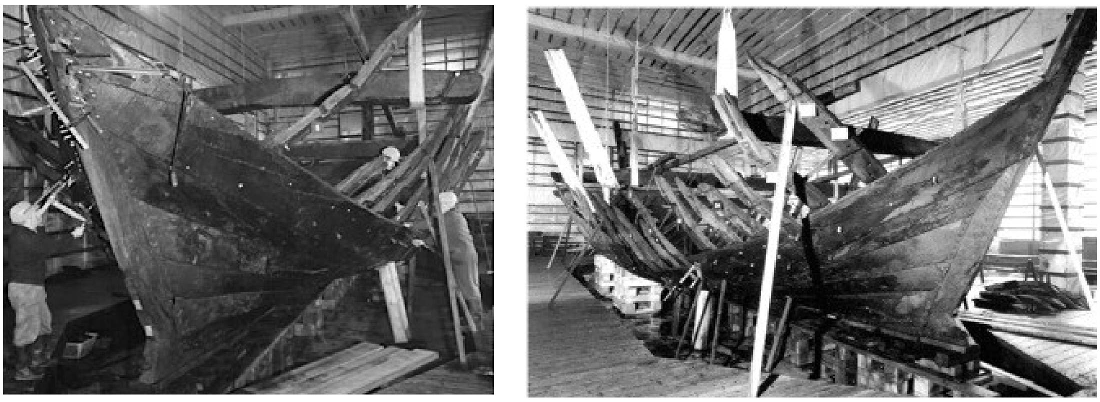

Figure 5-3: Reconstruction in the German Maritime Museum, 1972-1979 (Günter Meierdierks/DSM)

According to Lahn, 45 tons of wood was to be put together. Over several years, the team reconstructed the *"medieval puzzle"* under difficult working conditions: almost constantly 100% relative humidity in the room. Building the starboard side, turned out to be the most challenging task, since the parts were not labelled during the excavation due to poor visibility conditions underwater. On the other hand, the port side was much easier, since all timbers were numbered (see Figure 5-3).

[115] Disodium hexafluorosilicate and zinc (II) chloride
[116] Retired boat builder
[117] Ship building engineer
[118] Helmut Bohnsack and Peter Fromlowitz
[119] Kogge-Halle in German

After almost eight years of intensive work, the ship was ready for the next step in 1979. After reconstruction the *Bremen Cog* measured about 24m in length; 7m in width and 4m high from keel to gunwale, and 7m high to the top of the castle-deck (Hoffmann, 2011, p. 153).

5.1.2 Conservation and presentation

5.1.2.1 Wood assessment and first conservation plan

The *Bremen Cog* is entirely made out of oak (*Quercus*). The trees felled at the latest in 1378 and based on the recent dendrochronological analyses, the wood originates from the Bremen area, not from Weser Upland, as the first results suggested (Daly, 2017) (Belasus et al., 2021). The common hypothetical construction date is 1380 (Liese and Bauch, 1965) (Bauch et al., 1967) (Klein, 2003).

The conservation plan of the *Bremen Cog* was set up by three professors from the University of Hamburg, Walter Liese[120], Detlef Noack[121] and Hans-Hermann Dietrichs[122]. Based on the literature and tests run on samples from the ship, the experts advised a conservation treatment with Polyethylene Glycol (PEG) 1000 at 60% concentration for a period from 20 to 30 years, in complete immersion (Noack, 1969, p. 145).

In 1979, Dr. Per Hoffmann[123] was hired by the German Maritime Museum to supervise the conservation and set up a laboratory.


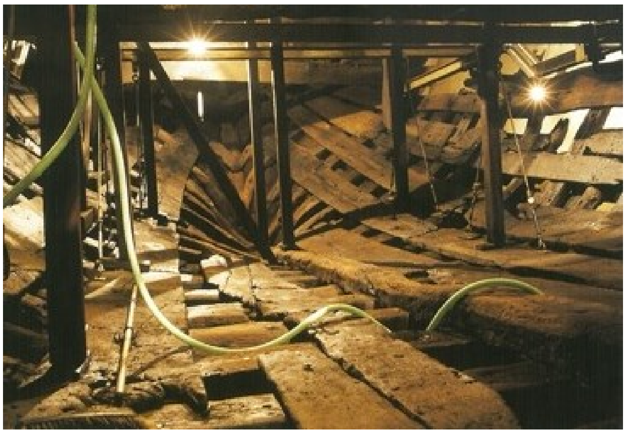

Figure 5-4: Conservation tank (left) (Egbert Laska/DSM) and pumping system (right) in the German Maritime Museum, 1980-1999 (Per Hoffmann)

[120] Professor Walter Liese (1926- 2023) wood biologist - Head of the Institute of Wood Biology and Wood Preservation
[121] Professor Detlef Noack (1931-) wood physicist
[122] Professor Hans-Hermann Dietrichs (1928-1981) wood chemist
[123] Wood chemist, Head of Conservation at the German Maritime Museum from 1979 to 2008

5.1.2.2 Two steps method

When Hoffmann took his assignment in 1979, he decided to switch to PEG 1500 based on the experience of his Danish colleague in Copenhagen Kirsten Jespersen[124] (Hoffmann, 2013, p. 46). Samples were taken throughout the entire conservation process, enabling Hoffmann to adjust the treatment, as describing his work as *"full scale experiment"* (Hoffmann, 1983) (Hoffmann, 1986a).
The stainless-steel tank built around the ship held 800,000 litres of liquid (Hoheisel, 1985) (see Figure 5-4). As the PEG 1500 was not penetrating as expected into the wooden core, Hoffmann decided to use another type of PEG with a lower molecular size. This method was later called two-steps treatment (Hoffmann, 1986b).

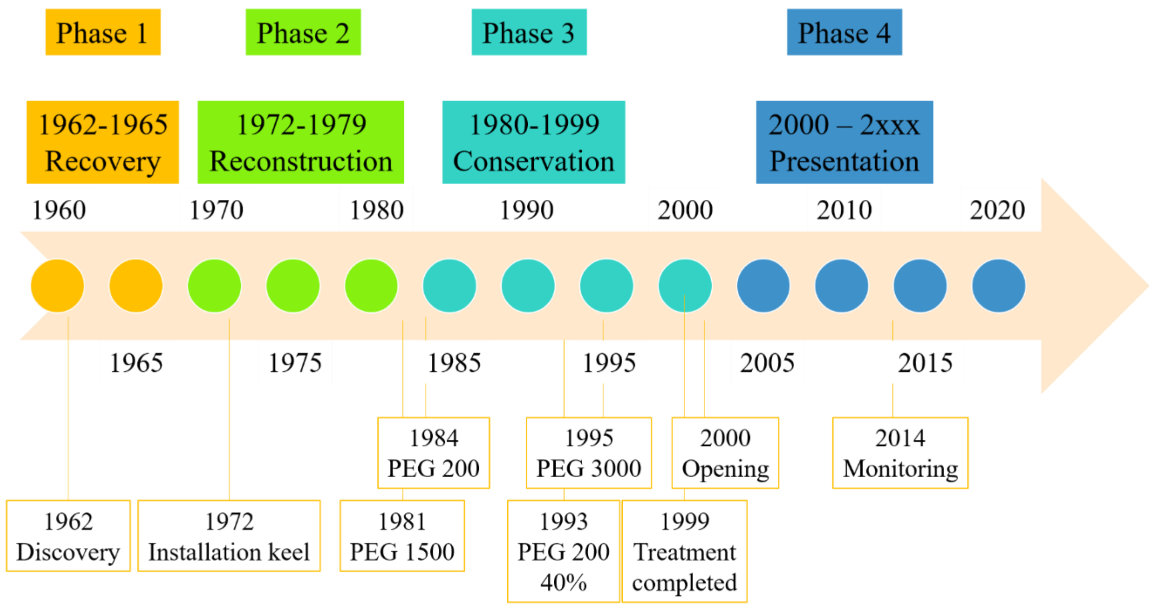

Figure 5-5: Overall chronology Bremen Cog Conservation (A. Colson)

In summer 1985, the solution was switched to PEG 200 for stage 2 (Hoffmann, 2013, p. 49) (Hoffmann, 1986a). After reaching 40% PEG concentration in water solution and two years of discussion with the local water company about disposing the old solution, stage 3 started in November 1995 with PEG 3000 and reached 70% shortly before Christmas 1999, after 19 years of conservation.
The ship was cleaned from her remaining PEG shell over spring 2000, the surface was smoothed using a heat gun, brushes and dried for about six months.
For an overall timeline on the treatment from the *Bremen Cog* see Figure 5-5.

[124] At the time Head of Waterlogged Wood Conservation unit, in Copenhagen

5.1.2.3 Suspended support

The presentation was planned by engineers in applied mechanics and naval architecture from a Berlin University[125] (Hoheisel, 2003). The main requirement was access to all ship's parts for both the public and specialists, nothing was to obstruct the global view (Hoheisel, 1969). In other words, the priority was set on an aesthetical presentation and to display a ship standing apparently *"effortless"* in the exhibition (see Figure 5-6). The presentation design was even described as *"a kind of suspended construction (…) by which the main load of the cog is to be held from above and which is to be supported from the roof of the future exhibition building"* (Fliedner, 1974, p. 79).

A series of supports were fixed to the ceiling as well as under the keel to avoid any additional elements around the hull. The weight distribution was very precisely calculated[126]. The implementation of two longitudinal and eight crosswise steel supports was designed to maintain the ship in shape, creating an inner brace to support her during conservation, as well as during the later drying process and beyond (Hoheisel, 1969, p. 171).

Figure 5-6: Bremen Cog in the exhibition around 2000 (DSM)

5.1.3 First surveys

5.1.3.1 Stereo camera survey 1980

The *Bremen Cog* was surveyed a few times. The first survey used photogrammetry* (see 4.1.3.2 p. 73 for technical details) and was conducted by the engineer Helmut Seeberg and supervised by Professor Bernhard Wrobel from the Institute of Photogrammetry and Engineering Surveys, University of Hanover.

[125] The university exact name could not be found in the literature

[126] The corresponding tables and detailed calculations con be found in Hoheisel's publication

In 1980, the engineering survey took a few days using a Zeiss SMK 120 metric camera, heavy equipment that had to be transported to every position. 80 analogue images, on glass plates, were taken of the ship from various angles (Wrobel, 2020) (Wiggenhagen et al., 2004). The assessment was made by hand with a Zeiss Stereoplanigraph C8 and took several months[127].

The results were lines of 10 profiles of the ship's hull depicted on 1:20 scaled drawings. Additionally, 2D representations from starboard, portside and from the top were produced for the ship's documentation (see Figure 5-7).

The other technical drawings made at the time are not based on the photogrammetry acquisition and depict an idealized shape designed by Lahn (Lahn, 1992).

The glass plates with the original photographs still exist and are currently stored at the Institute of Applied Photogrammetry and Geoinformatics (IAPG) in Oldenburg.

[127] Interview with Professor Wrobel September 2020. A. Colson – confirmed by Professor Thomas Luhmann

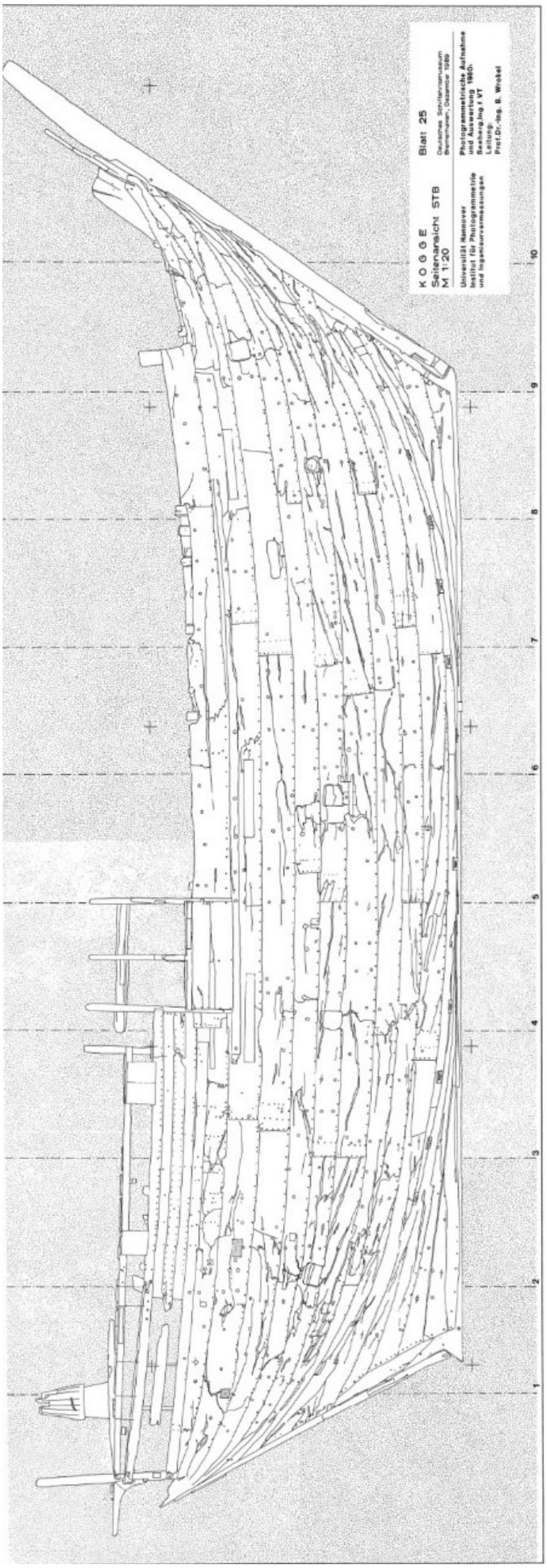

Figure 5-7 : 2D representation of the Bremen Cog (1980) (Wrobel/Seeberg) (Kiedel and Schnall, 1985, p. cover).

5.1.3.2 Digital photogrammetry 2003

The second acquisition was conducted by Dr. Manfred Wiggenhagen and his colleagues, from the same institute as their predecessors at an interval of over twenty years (Wiggenhagen et al., 2004). By then, the technology had changed from analogue to digital.

The goal was to compare the data from the first acquisition before conservation with the current state 23 years later, after the treatment. The acquisition was conducted using two digital cameras: a 6-megapixel Nikon D100 (40 images) and 5-megapixel metric camera Rollei D7 (60 images). The pictures were taken from the ground floor and the first floor of the 'Cog Hall' at a range of 2.5 to 6m.

Since the first acquisition provided profiles of several sections of the hull, the same lines had to be measured again on the *Bremen Cog* (see above 5.1.3.1.). For that reason, 20 lines were marked on the outside of the ship, both port and starboard, for the 10 profiles on each side. The object points were fixed lines: in total 347 points. Additionally, reference points were fixed on the hull: 105 tie points (see Figure 5-8).

The quality was quantified as following: precision of ±0.5mm for the tie points, which were automatized, and ±3mm for the object points, acquired manually. During the data processing, 99 images were used, and 340 object points could be measured, with every point measured on at least three images.

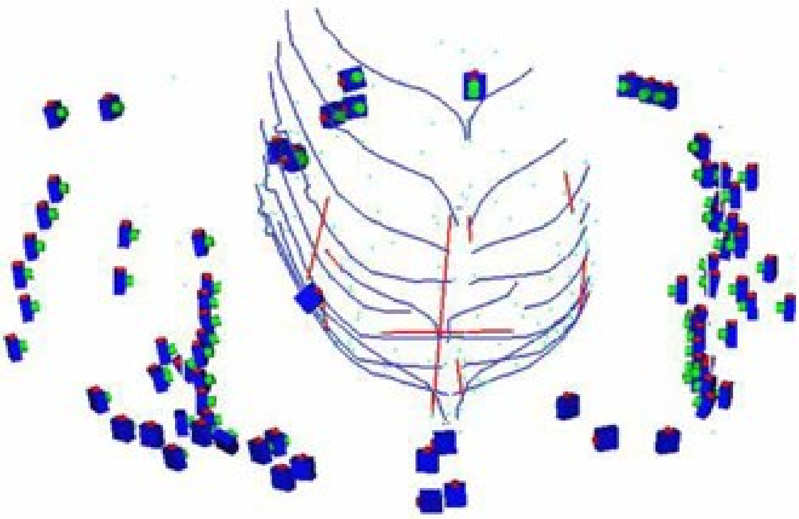

Figure 5-8 : Camera station and profiles (Wiggenhagen et al. 2004).

Based on the quality assessment, in the worst case an accuracy of 13.4mm was reached, fitting with the requirements set up by the museum of ±10mm to 20mm[128]. It took about 10 hours to set up the targets on the ship, but we have no information about the complete duration of the acquisition.

[128] Set up by the German Maritime Museum according to Wiggenhagen

Unfortunately, the results and the data have been lost by the German Maritime Museum, and no copy has been kept at Hannover University[129]. After many efforts from the author to search the museum's archive and library, no trace of this work has yet been found.

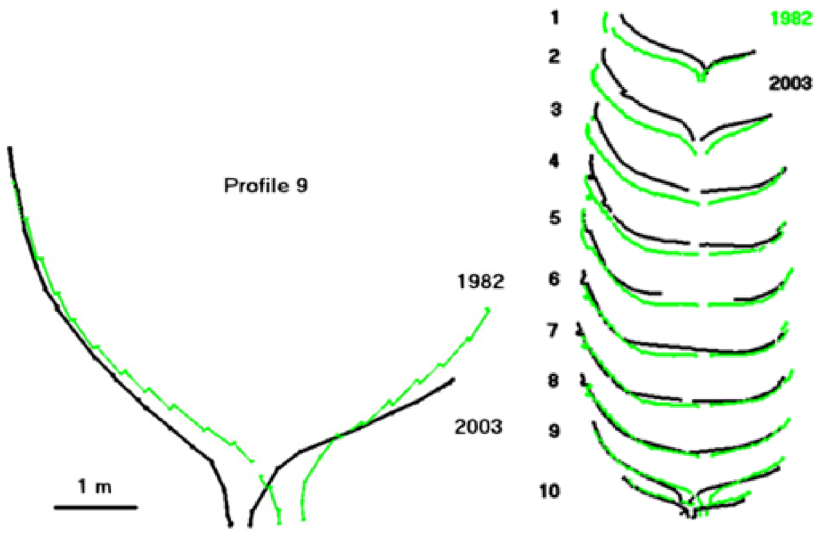

Figure 5-9: Distortion in profile 9 (left) and comparison of profiles (right) (Wiggenhagen et al. 2004).

The output was a deformation* in the range of 10 to 25cm, detected by comparing the data from 1982 and 2004. In the horizontal planks the difference was up to 20 cm, but the ship moved mostly in the lower part toward the inside and rotated in the other direction (Wiggenhagen et al., 2004) (see Figure 5-9).

5.1.3.3 Laser scanning 2009

In conjunction with the design of a new metal support, the inner side of the ship was scanned to aid in the manufacture of steel *"bending resistant frames and stringer variant"* (KSF Ingenieurbüro, 2009)[130]. The data was archived by the engineering office KSF in Bremerhaven, contracted to assist the museum in that project. No information or documentation on the acquisition was left behind. Apparently, no coordinate system was used, and the type of equipment was also not mentioned. Most likely, a terrestrial laser scanner was used.

5.1.4 Motivation(s)

5.1.4.1 Correction, stabilisation, and presentation

In May 2000, the 'Cog Hall' opened to the public inaugurated by the Federal President of Germany Johannes Rau[131] and after almost 40 years the medieval ship was finally presented.

[129] As agreed in the contract between the two Institutions
[130] Unpublished information
[131] Johannes Rau (1931-2006) President from 1999 to 2004

Only one year later the first deformations were observed, which started to worry the conservator and the museum board (Hoffmann, 2011). As the hanging presentation system turned out to be inadequate, a scientific committee was put together with experts from Denmark, Germany and the DSM (Hoffmann, 2010). The project phase was named *"Correction, stabilisation and presentation"*, showing how aware all participants were about the severity of the situation. Hoffmann mentioned three options: 1) disassembly and reassembly of the ship according to the reconstruction plan of Werner Lahn; 2) correct the deformed hull according to Lahn's plan, insert a metal support inside the ship and anchor it to the floor in order to stabilise the whole; 3) stabilise as it is.
Taking a decision on such a delicate matter demands courage. Hoffmann and his colleague were facing an ethical dilemma, which is clearly stated in his publications. The survey conducted in 2004 was required by the scientific committee but never used by Hoffmann[132] (see 5.1.3.2 Digital photogrammetry 2003). Nevertheless, in 2006, option 2 was finally agreed upon by the committee and the museum board (Hoffmann, 2011, p. 155).

Figure 5-10: Bremen Cog metal cradle, before 2016 renovation (DSM).

In February 2007, the hull *"corrections"* were conducted with 33 metal elements with mounted rods to exert pressure locally (16 on starboard side and 17 on portside) connected to 100 points, the wood was in its 'original' position after a few days, reports Hoffmann, see the red metal elements on Figure 5-10.
In October 2008, concrete was poured to raise the floor level under the ship, to provide more strength to the cradle and the inner planking, since the original steel supports were removed from inside the ship (Hoffmann, 2011, p. 158).

[132] Personal communication with Per Hoffmann.

The same month, Per Hoffmann retired and left behind a written concept[133] which was yet to be implemented. In 2009, a laser scan was performed on the inner hull from inside the ship, to gather data and manufacture a new metal system (see 5.1.3.3). This system would never be built (see Figure 5-11).

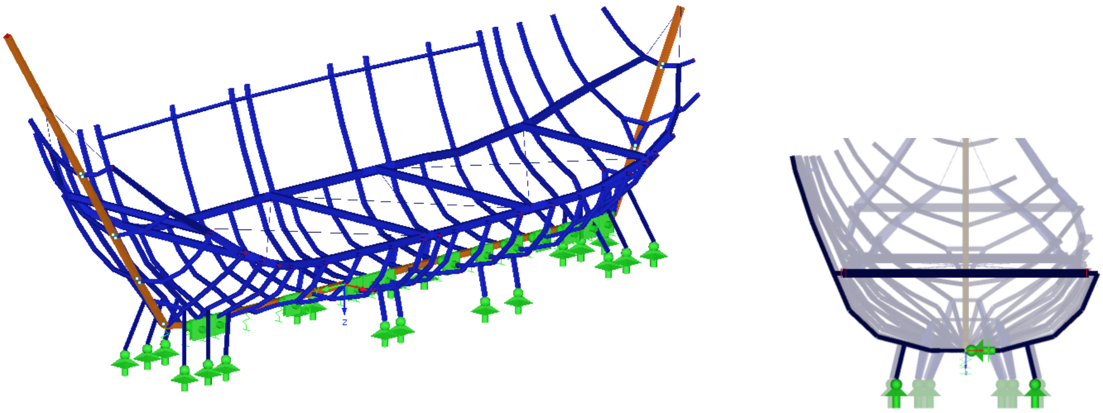

Figure 5-11: Bremen Cog new support (KSF Engineering Office).

5.1.4.2 Long-term preservation

Hoffmann was gone and time had passed, the *Bremen Cog* was no longer the centre of attention at the DSM. Access to the hull became very limited because of the concrete floor and a lot of dismantled wooden elements were stored in the exhibition hall without support.

In November 2013, a scientific committee meeting was organized with experts from several fields: Archaeology, Conservation, Museum Design, Heritage Protection, and Conservation Science. The necessity of a new support was indisputable, but the need to collect more information on the ship's current state was raised. The committee was leaning towards option 3: to stabilize the ship as she was and work around the current shape[134].

These discussions led to the first idea of a deformation monitoring system to keep an eye on the ship over time and collect more information to design a new support system.

As a matter of fact, the *Bremen Cog* is not the only archaeological wooden ship on display in a museum, nonetheless, the challenge of putting ships on display is not trivial (see 4.3 Spatial monitoring of archaeological ships p 85).

Although an enormous amount of resources, of both financial and human nature, were allocated to the project over several decades, the question of long-term preservation was neglected and not included in the project plan, see the workflow presented in 1.1.3 Long-term preservation p. 27.

[133] The written concept was never made available to the author and no signs of such document could be find at the museum.

[134] Notes from the author, who participates personally to the meeting.

Designing a spatial monitoring system to understand the hull's movements and geometrical changes appeared to be essential and in line with principles of preventive conservation* (see 1.2.2 Preventive conservation p. 31).
Thanks to the study conducted in 2004, suggestions of distortions and deformations of up to 20cm were already established. However, the ship was not measured after the "*correction*" and so the need was justified (Wiggenhagen et al., 2004).

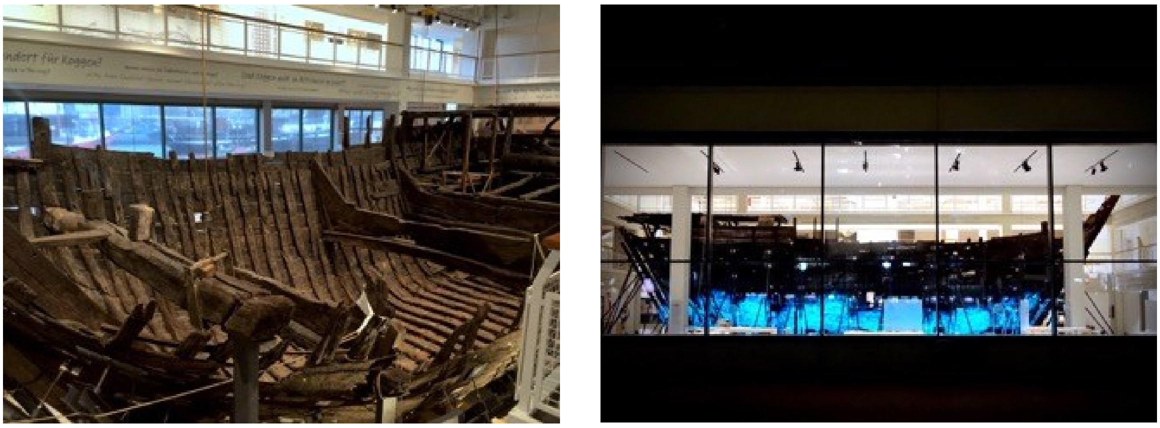

Figure 5-12: View toward the harbour (left) (A. Colson) and night view from the outside (right) (Igelhaut&vonGrote 2017)

5.2 Aims

5.2.1 Restrictions and constraints

The German Maritime Museum is located in the city centre of Bremerhaven behind the dike on the mouth of the river Weser, between the North Sea and the old harbour. This part of the German coast is subject to tides[135] of the biggest amplitude, where the tidal range is larger than 4m[136]. The museum is built on a narrow land strip considered an intertidal[137] zone, and the influence of the tidal range is proven, measured and carefully monitored[138].
The medieval ship is presented in the 'Cog Hall', a building designed specially by the famous German Architect Hans Scharoun to present the ship and to offer the best experience to the visitor and the passers-by (see Figure 5-12). The whole museum facility, including the Dietrich Bangert building (2000) has been under heritage protection since 2005[139].

[135] Tide: periodic rise and fall in the level of the water in oceans and seas as a result of gravitational attraction of the sun and moon and the rotation of the earth.
[136] http://www.coastalwiki.org/wiki/Coriolis_and_tidal_motion_in_shelf_seas (last visit 12.03.2023)
[137] Intertidal zone is the area of the shore that lies between the highest normal high tide and the lowest normal low tide. It is also called littoral zone.
[138] Surveying done by the Bremerhaven Harbor Authorities - Bremenports GmbH
[139] https://www.bremerhaven.de/sixcms/media.php/94/Denkmalliste+Stand+24.pdf (last visit 12.03.2023)

The room is rectangular and oriented north-east towards the old harbour of Bremerhaven with a huge window front and a south-west opening to the rest of the museum.
On the ground floor the visitor can explore all around the ship. The first floor is built on three sides to ensure a full picture from the window front and a view on the starboard side, both from inside and outside the museum. The second floor is a narrow gallery showing the ship from all four sides.
The museum is open every day in summer and closed on Mondays in winter. Opening hours are usually from 10:00 to 18:00 with some exceptions. A night security service ensures that the museum is guarded at all times, which makes potential night work possible.
The room hosts not only the ship, but a permanent exhibition on the history of the *Bremen Cog* and additionally some installations from temporary exhibitions. This means that the disposition of show cases and other installations is subject to change and never fixed, which constitutes another constraint.
Since 2016, the new permanent exhibition includes stapled wooden beams placed in front of the ship around every metal support, which conceals the view of the hull (see Figure 5-13).

Figure 5-13: Bremen Cog exhibition situation after renovation (A. Colson)

During the time of the project no surveyor or 3D measuring expert was employed at the museum. The board of directors specified that employing additional staff with these skills set was not planned[140].

[140] Personal talks with Prof. Dr. Sunhild Kleingärtner and Dr. Ursula Warnke – March 2016

The question of the necessary expertise to set up a spatial monitoring system was central, and the know-how had clearly to be acquired externally through cooperation with suitable specialists and institutions.
The staff involved in the project was composed of one person (the author) in charge of preventive conservation for the whole museum collection (2013-2015), and from 2016 to 2019 as a research fellow. At the time of writing this thesis, the museum was employing two permanent staff member, one conservator and one museologist in charge of the whole collection, storage facilities as well as the exhibition area.

5.2.2 Setting up goals

While starting the monitoring project, the goal was to find a technique or methodology to acquire geometrical changes at least twice a year, to enable the comparison of data over time, and to correlate this information with climate data.
The solution had to be non-invasive, to comply with the conservation ethics, or, if we were to install more equipment on the *Bremen Cog*, at least reversible (see 1.2.2 Preventive conservation p. 31 and 2.4.1 Guardians of ethics p. 48). The targeting had to be as discreet as possible so as not to disturb the visitors' experience and not disrupt the aesthetic of the artefact.
The project started with a catalogue of requests, ideas and needs, but a desired accuracy was not stated at the beginning. The only requirement was to make the measurement as precise as technically possible. However, the monitoring of the warship *Vasa* showed that detecting movements of about 1mm was technically feasible (see 4.3.2.4 p. 91) and that the ship moves about 1 to 3mm a year. Considering that the *Bremen Cog* and the *Vasa* were both conserved with polyethylene glycol* (PEG), similar changes could be expected on the *Bremen Cog* and need to be monitored. Therefore, 1mm detection was defined by the author as the reference value.
For the longer term, the goal was to use the data at a later stage to calculate structural and mechanical changes, in order to design a new adequate support.
The spatial monitoring set up was planned to never make the room inaccessible to the public or disable permanent and temporary exhibitions.
Finally, the resources available at the DSM had to be taken into account. The final solution had to be as cost-effective as could be with the lowest investment possible. The equipment, staff (internal and external) and the time dedicated to the monitoring were part of the costs' overview, which had to play a role in the final decision making. The minimum cost for the best results fitting to the long-term preservation goals of the *Bremen Cog* would be favoured.

5.3 Preliminary trials – COSCH (2014-2016)

5.3.1 COSCH project

In spring 2014, Dr. Ursula Warnke[141] was contacted to participate in the European COST Action TD1201[142]. Colour and Space in Cultural Heritage (COSCH) was launched in November 2012 for a period of four years. COSCH aimed to *"promote research, development and application of optical measurement techniques – adapted to the needs of heritage documentation"*[143].

At the time, the COSCH working groups leaders decided to call for case studies. The aim was for a deeper understanding of the use of each selected technique and to gain an overview of the related processes of applying optical and spectral documentation techniques for cultural heritage.

The *Bremen Cog* case study was designed by the author. The case study proposal was selected together with six others. Among all the proposed studies, the *Bremen Cog* was, in terms of size, building a bridge between standard museum artefacts (coins, vases, wooden icons) and sites (citadel) ("COSCH Case studies," 2014).The case study was coordinated by the author and conducted between 2014-2016. The participation in the case study of the COSCH framework offered the chance to discuss and to receive feedbacks from European experts during five management committee (MC) meetings, until the end of the COST Action. Secondly, experts participating in the case study were eligible to apply to short term scientific missions (STSM), which enabled their travelling expenses to be funded ("COSCH exchange program," 2016).

Being part of the COSCH action provided the opportunity to benefit from a network of scholars and experts who challenged our aims, but most of all to conduct the first attempt to acquire the ship three-dimensionally. The scientific relevance was quickly recognized among European colleagues, and this helped to convince the museum's board of directors of the importance of such an initiative. Preliminary tests were performed to find out which method would be the most suitable and to refine the aims of a final spatial monitoring system.

The goal of the COSCH case study was to test different technologies, to monitor the deformation processes as an on-going project and continue to check on the ship during the renovation works (2015-2016).

Based on the literature survey and the experiences of other projects, it was decided to choose three technologies: 1) Structure-from-Motion (SfM); 2) Laser scanning; 3) Total station.

[141] Former Director of the German Maritime Museum from 2006 to 2017.

[142] European Cooperation in Science and Technology, is "supporting trans-national cooperation among researchers, engineers and scholars across Europe" http://www.cost.eu/about_cost (last visit 12.03.2023)

[143] https://cosch.info/project.html (last visit 12.03.2023)

The table summarizing the relationship between the measuring methods, the object's size and the accuracy helped to give a clear overview (see Figure 4-5 Relationship between measuring methods and object's size (Luhmann et al., 2020, p. 5) p. 70).
The first acquisition used structure-from-motion (SfM)* and was conducted by the researcher Julien Guery working for the private company Captair, France. The second test applied the use of a laser scanner* performed by the University of Applied Science in Mainz (i3Mainz), Germany, Stefan Mehlig and Carina Justus. The final trial involved the use of a total station* conducted by a ship archaeologist, Massimiliano Ditta, from the University of Southern Denmark Esbjerg. Additionally, Levente Tamàs, associated professor from the robotics and nonlinear control research group at the Technical University of Cluj-Napoca, Romania, conducted some tests to fuse the produced heterogeneous data together (Colson and Tamas, 2017).
The set-up of each test and results will be presented in the following paragraphs. The author is reporting her colleagues' work in her capacity as case study initiator and coordinator.

5.3.2 Structure-from-Motion (SfM)

5.3.2.1 Set up

Considering the constraints in the exhibition (see above 5.2.1), structure-from-motion (SfM) offered a flexibility for the image acquisition that was advantageous, see 4.1.3.2 Image based p. 73 for a detailed explanation of the technique. It is also a common technique used for the documentation of ship timbers and large structure in maritime archaeology (Colson, 2017).
The first short term scientific mission (STSM) was conducted in October 2014. Julien Guery[144], spend one week at the DSM.
During the acquisition campaign the following equipment (hardware and software) was used, mostly provided by Captair[145]:
Canon EOS 5D MarkIII, full frame with 50mm lens
Canon IXUS RGB, compact camera with 24mm lens
Canon IXUS NIR (Near InfraRed), compact camera with 24mm lens
Nikon D300, APSC with 18mm equivalent 27mm camera lens (DSM)
Agisoft Photoscan software[146]
All the photographs were taken using a camera tripod.
The targeting was made using six black and white circular targets and glued with tape on to the concrete pillars and on the metal cradle of the ship, as suggested by the colleagues from i3Mainz.

[144] at the time PhD candidate University of Burgundy (Dijon)
[145] French SME offering service in 3D Documentation of Cultural and Natural Heritage
[146] The version of the software is not known by the author and is not stated in the report

Their coordinates were measured by hand separately and documented. The acquisitions were made in the evenings to avoid the light coming through the front window (Guery, 2015). A second campaign was conducted in March 2015 by Julien Guery.
Another SfM* acquisition was conducted in April 2016 by Massimiliano Ditta with the Nikon D300 owned by the museum following a similar approach.

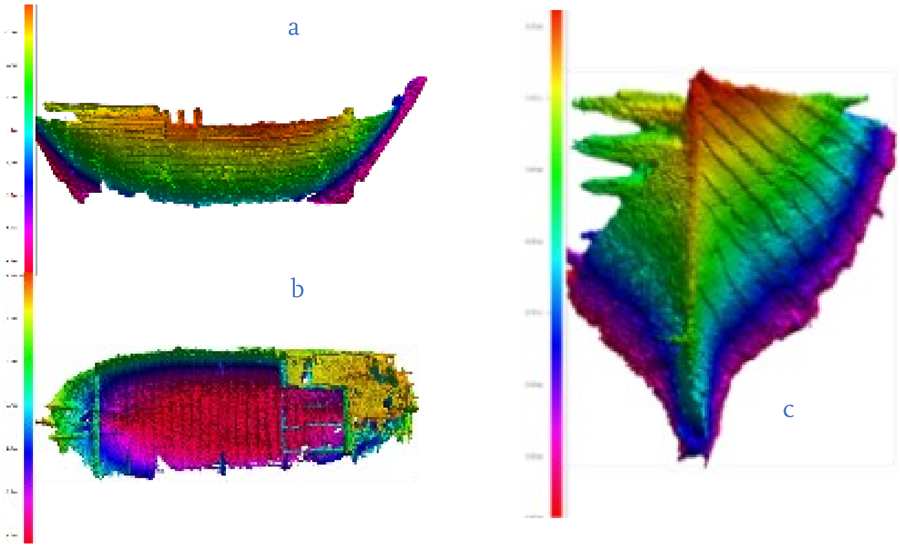

Figure 5-14: Digital Elevation Model-(J. Guery) - 2014

a) starboard side; b) top view; c) bow

Targets printed on A4 paper sheets were place around the ship: 14 on the ground floor, 18 on the first floor and 5 on the second floor, for a total of 37 targets.

5.3.2.2 Results

The results from the mission showed that the best time to make photographs was in the morning or in the evening to avoid backlight.
About 200 pictures were used to compute the 3D model and provided a 3D dense point cloud of 7.7 million points. A digital elevation model of the ship was also produced with a resolution* of 5mm (Guery, 2015).
The final post-processing was conducted in Guery's office back in France, because of a lack of appropriate computer capacity at the DSM.
The Nikon D300 camera owned by the museum was not performing as hoped, according to Guery, and it was planned to purchase a new fixed lens.
Massimiliano Ditta on the other hand, made about 650 pictures for an acquisition time of 1.5 hours and a processing of about 12 hours.

5.3.3 Terrestrial laser scanning (TLS)

5.3.3.1 Set up

One month after the SfM* acquisition a terrestrial laser scanning* campaign (see 4.1.3.1 Laser based p. 70 for technical details) was conducted by the University of Applied Sciences Mainz- Institute for Spatial Information and Surveying Technology i3Mainz. Two engineers, Carina Justus and Stefan Mehlig, spent three days at the DSM. The first day was dedicated to total station* acquisition to measure the reference points installed during the SfM campaign and adding more targets to be able to build a coordinate system. The coordinate system was to play an important role in the later data evaluation and data fusion (see 4.1.2 Building a framework p. 68).

During days two and three the *Bremen Cog* was scanned completely from the outside and inside using all three stories of the building. In total 29 positions were necessary to scan the whole ship. The equipment used was a Leica ScanStation P20[147]: time-of-flight enhanced by Waveform Digitising (WFD) pulsed laser scanner with an integrated camera (see Figure 4-7 p. 72).

Additionally, a structured-light scanner was tested to acquire the geometry of the lower part of the bow.

5.3.3.2 Results

At the time of writing this thesis, there was no report provided by i3Mainz about the results of the campaign. The processed data without any documentation was partially handed over to the museum and no conclusion could be derived from this campaign. A short description is available on the university website in German[148].

5.3.4 Total station (TS)

5.3.4.1 Set up

The second short-term-scientific-mission (STSM) was performed by Massimiliano Ditta, ship archaeologist[149], for a period of three weeks in April 2015. Ditta is an experienced user of 3D technologies, namely total station* (TS) and SfM*, in the context of 3D documentation of archaeological ships. The equipment used was a total station Flexline Leica TS06 owned by the Museum.

[147] https://www.laserscanning-europe.com/sites/default/files/redakteur_images/leica_scanstation_p20_dat_de.pdf (last visit 12.03.2023)

[148] https://i3mainz.hs-mainz.de/news/2014/11/24/3d-aufnahme-der-bremer-kogge-1.html (last visit 12.03.2023)

[149] University of Southern Denmark

The selected methodology used the total station* and a plug-in for the 3D CAD-software Rhinoceros, which enables the operator to control all measured points on a laptop in real-time. Since the total station was used indoors and the GPS sensor could not be used for orientation, the existing coordinate system used for the SfM* and 3D scanning* campaigns had to be extended and more coordinate points were added (see 4.1.3.1 Laser based techniques p. 70 Total Station (TS) for technical details). For each recording station at least one coordinate point was added between the instrument and the *Bremen Cog* in order to gain orientation in space. Objects points were defined and were classified in two categories: 1) existing targets on the hull used in former surveying campaigns also called 'marked points' and; 2) selected points on recognizable wooden parts also called 'timber feature points'. A total of 196 object points were measured: 144 points on the outer hull[150] and 52 on the inside[151].
The total station* had to be moved several times and 22 recording stations were necessary to survey the whole ship: 16 stations on the ground floor, 2 stations on the 1st floor and 4 stations on the 2nd floor. The linear accuracy* was ± 2mm.

5.3.4.2 Results

It took Ditta about 16 hours to record the whole ship, after a few trials. Defining an acquisition protocol taking the constraints in the room (see 5.2.1 Restrictions and constraints) into account was not trivial. The measurement noise was below 1mm. It took two days of planning, 14 days of recording and five days of post-processing.

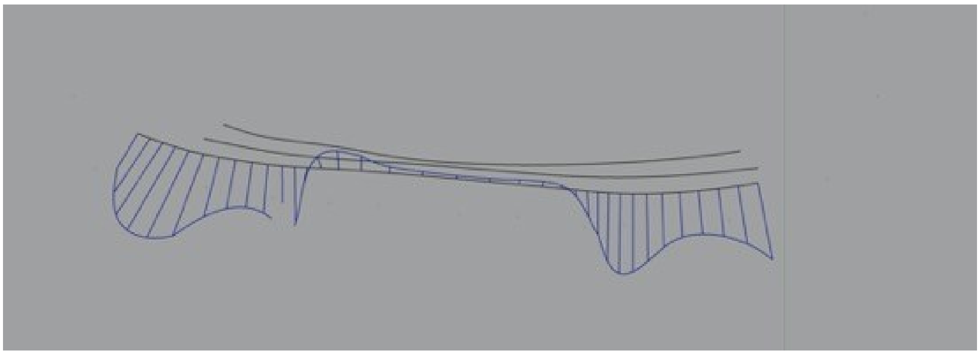

Figure 5-15: Curve of the upper strake (M. Ditta 2015)

The results could be visualized right away and vertical and horizontal cross sections could be selected to look at the ship's general geometry. Ditta manually chose object points laying on a continuous longitudinal line of planking, called a 'strake', this at several different heights. With Rhinoceros, the curves could be 'amplified' in order to emphasise the different direction the cross-section took along the strake (see Figure 5-15).

[150] 118 marked points and 26 'timber feature' points
[151] Only "timber feature" points

At that stage, no deformation* could be clearly identified but a horizontal 'wave' shape of the planks was observed (Ditta, 2015).

5.3.5 Data fusion

5.3.5.1 Set up

After collecting 3D data using three different methods, the idea was to combine them all together and to visualize them. Since the data are different in terms of accuracy*, standard deviation*, and density, the term 'heterogeneous data' is commonly used in this case. The specialist of 3D perceptions and robotics from Technical University of Cluj-Napoca in Romania, Dr. Levante Tamás, and part of the COSCH Network offered to look into the issue.

By combining data, the aim of the COSCH case study was to increase the chance of seeing any trends or geometrical changes in the ship and to get an initial overview and assess the gravity of the situation, but also to compare how the technologies performed.

In September 2015, Tamás spent one week in Bremerhaven funded by a STSM. He proposed comparing and processing the data using linear and nonlinear alignment algorithms, following a point-based and a patch-based approach.

The first step was to bring the data together and pre-process it, and for this a key point feature correspondence was used. The second step was to refine the alignment and process the data using iterative closest point alignment (ICP). The registration was performed with the software point cloud library[152].

During the processing the octree representation was used to relate points to each other.

The laser data from 2009 and 2014 were compared, as well as the SfM and total station.

The last step was the evaluation conducted with Euclidian distance metric helping to organize the points in space and highlight the changes between two points.

5.3.5.2 Results

After looking into the different data sets it turned out that the coordinate system placed during the SfM campaign was not sufficient to ensure a good alignment of the data during the processing. Tamàs found out that laser data from 2009 (see 5.1.3.3 p. 115) was concerning only the inside of the hull, although this was not known since not documentation existed.

[152] https://pointclouds.org

The conclusion of the STSM pointed out that bringing heterogeneous data together was not a trivial procedure when the campaigns were not planned precisely together, and the coordinate system not thought through. No deformations* could be clearly identified and comparing the data only provided information on the reliability of each data set and only put into perspective when looked at together.
Nevertheless, based on the data one hypothesis could be made: it looked like the areas where the metal element was in contact with the ship's hull tended to move less than the rest of the ship (Tamas, 2015).

5.3.6 Discussion

After COSCH case study, the question of the adequate spatial monitoring technique for the *Bremen Cog* was still unanswered. Although, visualizing the data and realizing how heterogeneous it is, was a real eye opener in terms of understanding the complexity of the issue, this failed to provide more information about the on-going geometrical changes or wood deformation*. The experience showed how challenging the set-up of a spatial monitoring system on an archaeological wooden ship in a museum exhibition can be.
Nevertheless, a few findings must be mentioned:

1) The Structure-from-Motion* acquisition under the described set-up turned out not to be precise enough and the data not reliable, because of the lower number of reference points. Yet, the acquisition time of a few hours made the image-based measuring systems interesting in this particular case (see 5.3.2 p. 122).
2) Although a terrestrial laser scanning* acquisition provides very precise measurement. The acquisition duration is very long, since a single acquisition took several days (see 5.3.3 p. 124).
3) A total station* is also a very precise instrument. However, in the way it was operated here, targetless, made almost impossible to measure the same exact point twice. On the other hand, it provided valuable information in a short time, and the data could be visualized (see 5.3.4 p. 124).

The need for more resources and further work became obvious. In 2015, the board of directors decided to finance a research project and announced a Phd-Fellowship. The position was filled by the author in March 2016. No budget was allocated to the project apart from personnel costs.

Meanwhile, a research project conducted by Dr. Mike Belasus was focusing on the *Bremen Cog*'s construction and consequently sailing abilities at sea[153]. A traditional boat builder, Dr. Pat Tanner, looked into all documentation available and made a systematic investigation to reconstruct the 'original' shape of the ship.

His evaluation based on the comparison between the drawings from the shipwright Werner Lahn before the conservation and the 3D scans from 2014, established a wood deformation up to 165mm (Tanner, 2016). Additionally, the wood quality was also studied[154] by Belasus showing the weakness of the ship construction, almost 50% of the hull's planks were repaired (Belasus and Daly, 2022). So, if the wood at the time of the construction was of poor quality and therefore the oak not mechanically performing like it should have, these properties will not have improved after conservation.

5.4 Spatial monitoring 2016-2019

5.4.1 Evaluation and monitoring concept

5.4.1.1 Collaboration with Jade University of Applied Sciences

The expertise in the field of surveying and geodesy to design a spatial monitoring system for the *Bremen Cog* appeared absolutely necessary after the COSCH project. Since the discipline was not represented among the staff at the DSM, an external partner was needed. After inquiring into different research institutes in Germany, Professor Thomas Luhmann answered positively to the request. Luhmann is the executive director of the Institute of Applied Photogrammetry and Geoinformatics (IAPG) from Jade University of Applied Sciences in Oldenburg. The geographical proximity, about 70 km between Oldenburg and Bremerhaven, as well as the expertise held by the IAPG team became the logical base for further collaboration. Since the project was meant to be maintained on a middle (five years) and long-term (20 years) perspective, securing a viable collaboration on both sides seemed to be a key element.

After clarifying on which modus operandi[155], the collaboration could take place, Heidi Hastedt, engineer in geoinformation systems and senior scientific staff at the IAPG, was appointed to the project. The goal was to work very closely together with the conservator (the author) to design a concept for the spatial monitoring of the *Bremen Cog*.

[153] Funded through Leibniz-Wettbewerbsverfahren – "Zwischen Nordsee und Nordmeer: interdisziplinäre Studien zur Hanse" lead by Prof. Dr. Natascha Mehler for the DSM.
[154] ERC Project „TIMBER" (2016-2021), University of Copenhagen, Ass. Prof. Dr. Aoife Daly. Grant agreement no. 677152
[155] The partnership contract initiated in 2017 was signed between the German Maritime Museum and the Jade University of Applied Science in Spring 2020.

5.4.1.2 Reassessment specifications and former datasets

The first step was the gathering of all the collected data on the ship's geometry over the last decades to conduct an evaluation. Parallel to the evaluation a series of meetings were organized, between Heidi Hastedt and the author, to define the specifications of the project (see 4.1.1.1 Typical workflow p. 66), as well as the author's goals and overall motivation to set up a monitoring system (see 5.1.4 Motivation(s)).

Based on the experience of the Vasa Museum (see 4.3.2 The warship *Vasa* (Sweden) p. 88), the defined threshold for movement detection was set by the author to ±1mm. Considering all the parameters, Hastedt concluded that none of the older data sets were suitable for spatial monitoring, since in most cases little to no documentation was left behind, making the data quality unknown. Furthermore, the lack of a global coordinate system made any reliable comparison impossible. Additionally, targets still present on the ship were also found to be inadequate (see Figure 5-18 p. 133).

Unfortunately, the only data collection conducted with a coordinate system in 2003 (see 5.1.3.2 Digital photogrammetry 2003), could not be found either at the DSM or in Hannover University.

In the light of this evaluation, it was decided to design a new monitoring concept[156] (Hastedt and Luhmann, 2018).

5.4.1.3 Choosing photogrammetry

The measuring system for monitoring the geometrical changes of the *Bremen Cog* was chosen based on the investigation carried out during the COSCH case study (see 5.3. Preliminary trials – COSCH (2014-2016)). A comparison of all technologies (TS, Photogrammetry, TLS, SfM) was presented by Hastedt in her report through a table showing the level of precision as well as the pros and cons of each method (Hastedt and Luhmann, 2018, p. 15).

In order to reach the requested resolution* of about 1mm and considering the constraints of the object as well as the museum rooms (see 5.2.1 Restrictions and constraints), the only two eligible techniques were total station* (TS) and photogrammetry*.

The Swedish experience using a TS showed that 120 person-hours are required for each acquisition of the warship *Vasa* (see 4.3.2.4 p. 91). In the case of the DSM, it was not realistic for the museum to assign two staff members for two weeks to monitor the *Bremen Cog*, as a result the acquisition duration became a very decisive factor.

[156] The report is unpublished but archived at the German Maritime Museum

After long discussions with Heidi Hastedt and Thomas Luhmann the only remaining option under the given circumstances was photogrammetry* combined with laser tracker. The technique was capable of reaching the requirements, the acquisition duration could be reasonably expected to be at maximum half a day, and it would require a maximum of two persons.

5.4.2 Monitoring set up *Bremen Cog*

5.4.2.1 Selected parameters

In 2017, Jurij Schmik conducted a feasibility analysis as part of his master's thesis at the Jade University of Applied Sciences, focusing on the spatial monitoring and deformation analysis of the *Bremen Cog* (Schmik, 2017).

Following the σ rule (see 4.1.4.2 Evaluation p. 78), it was established that the precision* (see Figure 4-12 p. 78) necessary for points on the object should be about 0.24mm (Schmik et al., 2018). Schmik conducted a laser scanning acquisition to perform preliminary tests virtually instead of doing them all onsite. With this method, the coordinate system was planned, and the single point precision needed to be reached was determined to be $S_{XYZ} = 0.14$mm.

During the preliminary tests, little care was given to the specifications, but rather on trying different methodologies (see 5.3 Preliminary trials – COSCH (2014-2016) p. 121).

In order to achieve the goal of 1mm deformation detection (see 5.2.2 p. 120), the Root Mean Square* (RMS) had to be between 0.23mm and 0.13mm (see 4.1.4.2 for explanation about RMS).

5.4.2.2 Coordinate system

As described in chapter 4 (see 4.1.2 Building a framework p 68) setting up a coordinate system is central and has a great impact on the results. The coordinate system is the backbone of the monitoring and builds a virtual three-dimensional box around the object, in which the exact location of defined points is known. Since these points are used as references and relied upon during the whole process, they need to be fixed and immovable. At the DSM, the *Bremen Cog* is exhibited in a heritage protected building, but it was authorized to drill holes in the walls to install the fixed points for the coordinate system. Holes have been drilled into the concrete walls and measuring bolts[157] have been installed (see Figure 5-16c). Some points have been reinforced with strong adhesive to ensure that no movements would occur.

[157] Wall bolt, survey point, forged from brass (Access May 2023) - https://shop.bohnenstingl.de/epages/Bohnenstingl-Spezialvermessungszubehoer.sf/en_US/?ViewObjectPath=%2FShops%2FBohnenstingl-Spezialvermessungszubehoer%2FProducts%2F0891

The bolts are fixed and never moved. In order to acquire their positions, a magnetic base[158] is screwed on each bolt. These bases are used with two different adapters: 1) for the laser tracker acquisition, Spherically Mounted Reflectors (SMR), a ball prism opening on one side and divided as a pie into six equal parts, 1.5-inch reflector (see Figure 5-16b); 2) and the other for photogrammetry, SMR targets, here a ball prism opening on one side with a reflective dot, 10mm diameter (see Figure 5-16a).
In total 20 reference points have been installed and distributed in the room (see Table 5-1 and Figure 5-17). The coordinate point locations were planned in order to enable 10 to 12 points to be seen in each photograph and at a maximum of 20 meters from the camera (Schmik et al., 2018, p. 45).

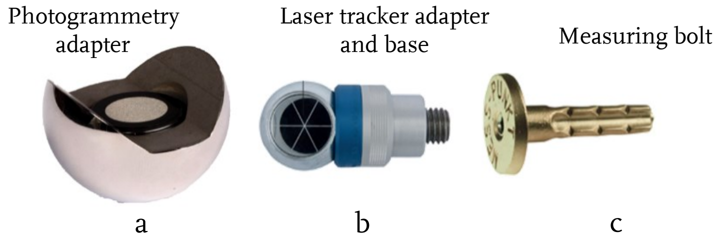

Figure 5-16: Targets coordinate system (Schmik 2017)

Point name	Side	Level
100	Starboard side	Ground level
101	Starboard side	Ground level
102	Starboard side	Ground level
103	Starboard side	Ground level
104	Port side	Ground level
105	Port side	Ground level
106	Port side	Ground level
107	Port side	Ground level
200	Starboard side	First floor
203	Starboard side	First floor
204	Port side	First floor
205	Port side	First floor
206	Port side	First floor
207	Port side	First floor
300	Starboard side	Second floor
301	Starboard side	Second floor
302	Starboard side	Second floor
303	Starboard side	Second floor
305	Port side	Second floor
306	Port side	Second floor
Total = 20 points	10 Port side 10 Starboard	8 Ground floor 6 First floor 6 Second floor

Table 5-1 : List of points from coordinate system – Bremen Cog

[158] Magnetic base with thread connections for ball prism (Access May 2023) - https://shop.bohnenstingl.de/epages/Bohnenstingl-Spezialvermessungszubehoer.sf/en_US/?ObjectPath=/Shops/Bohnenstingl-Spezialvermessungszubehoer/Products/1466.X

The XYZ coordinates of each point are measured and taken as references, these will always be referred to during the monitoring. The coordinate system has been acquired separately from the ship using a laser tracker Faro Vantage (technical details about the equipment see Laser tracker in 4.1.3.1 Laser based p. 70).

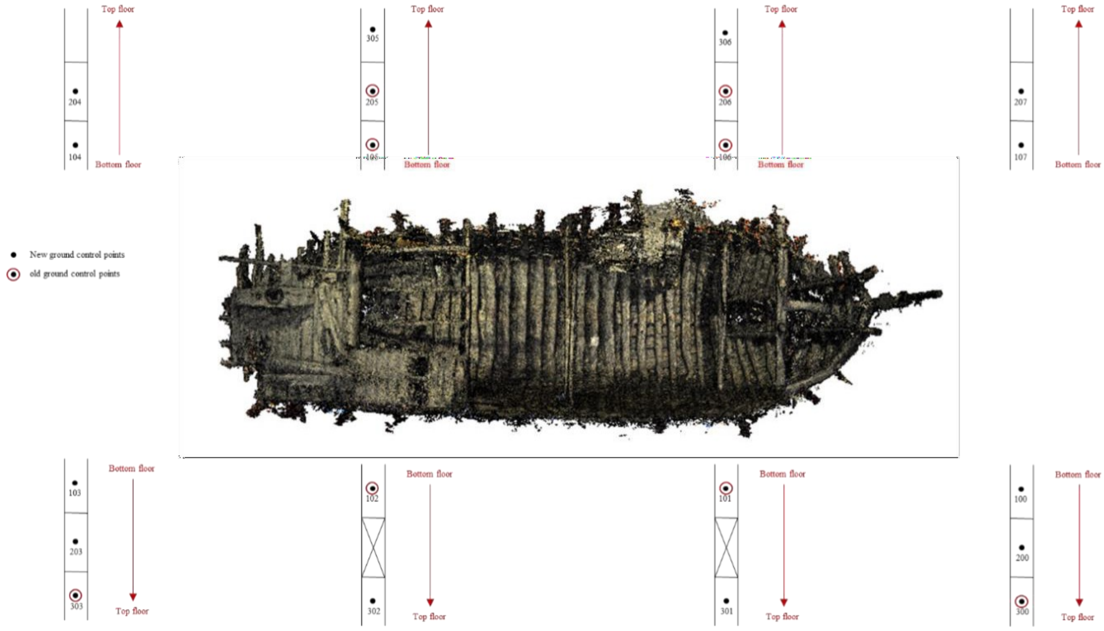

Figure 5-17: Coordinate system points related to the Bremen Cog (Hastedt and Luhmann 2018)

The laser tracker measurements are used to define a highly accurate 3D reference network that is used for photogrammetry* to ensure high quality of absolute orientation, and to be used as reference points for deformation analysis. The positions of the device during the acquisition are depicted in Figure 5-19 as well as in Table 5-1 and Figure 5-17.

5.4.2.3 Targeting

The step to signalize or place targets on the object of interest determines the results of the measuring and is therefore a crucial process (see 4.1.2.2 Targeting p. 69). Several points have been installed on the *Bremen Cog* itself, in the form of 10mm diameter reflected target stickers (see Figure 5-18). This diameter was chosen so as to not aesthetically alter the visitor’s experience and still fit with the accuracy* agreed upon with the engineers. The ethical principles of conservation are at the same time also respected. In order to avoid any contact with the original wood surface, Japan Papier Tangucho 11g/m2 was glued with Japanese wheat glue, Shofu Nori Powder, this process being completely reversible. The procedure was conducted by the museum’s conservator, at the time Siobhan Piekarek. In summer 2017, 122 targets were glued on the ship (Hastedt and Luhmann, 2018, p. 15).

Figure 5-18: Reflective object target: (Colson – 2018) - Left old target and right new one

Additionally, the metal structure around the ship was also used to temporally install 450 magnetic coded targets. Several standard coded scale bars of 0.7m up to 1.5m were placed close to the ship in several areas.

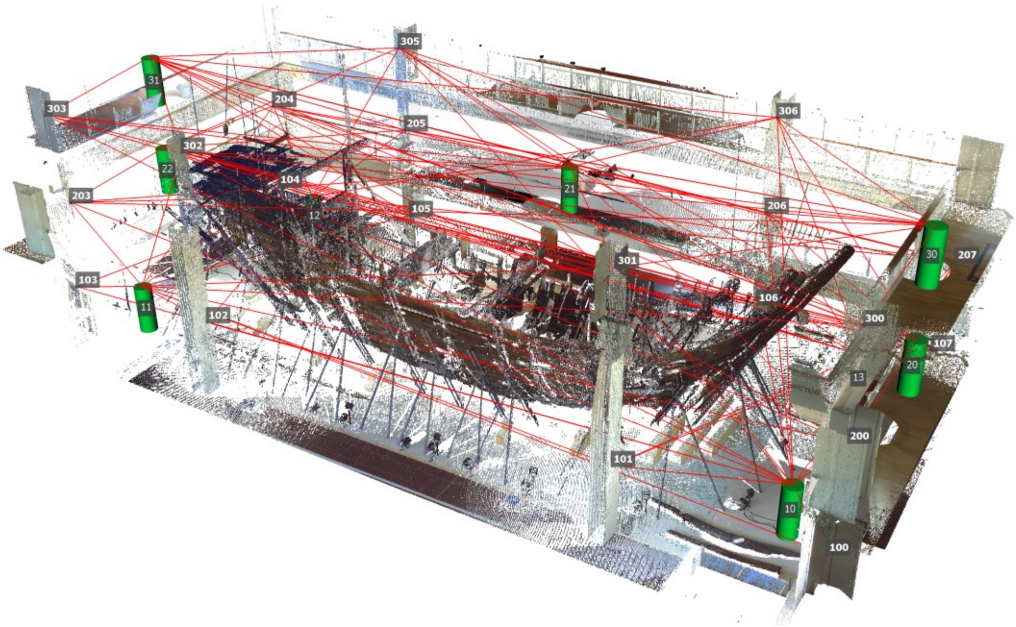

Figure 5-19: Coordinate system and acquisition stations (Schmik 2017)

5.4.3 Acquisition protocol

A two pages acquisition protocol has been formulated by Heidi Hastedt (Hastedt and Luhmann, 2018), serving as guidance if the acquisition was to be conducted by a third party. The acquisition takes about 2-3 hours and about 400 pictures (360 to 460) need to be taken. Considering the museum's location and the influence of the North Sea, the timing has to be chosen well and the tide calendar checked previous to any acquisition (see details under 5.2.1 Restrictions and constraints).

After discussion with colleagues from the Bremerhaven harbour authorities[159] it was decided to start the acquisition one hour before slack tide, when the water stands 'still' for a while before switching to either the ebb tide or the flood tide[160]. This means that the time window has to be strictly respected.

Before starting to take pictures, the equipment has to be carefully prepared. The magnetic bases must be installed in the 20 measuring bolts and the corresponding ball prisms must be placed as well. Everything needs to be installed at least 30 minutes before starting the acquisition for the equipment to accommodate to the environment (Hastedt et al., 2019).

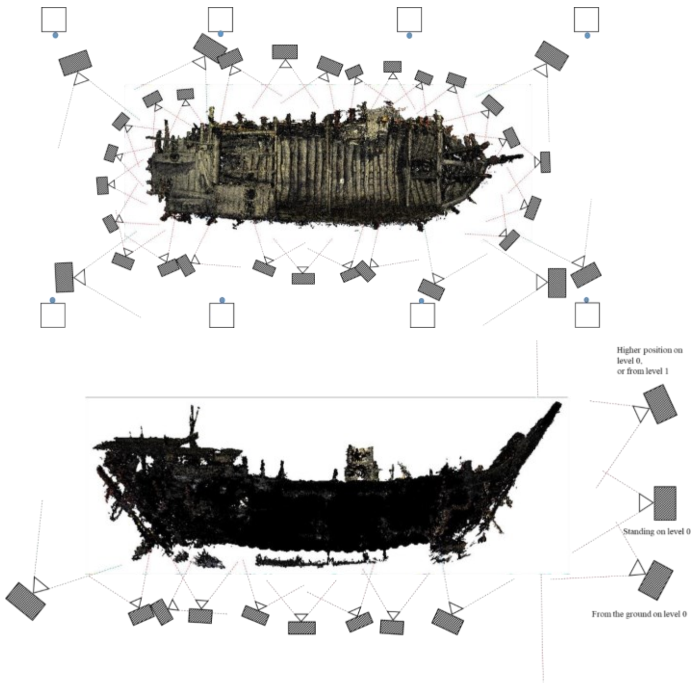

Figure 5-20: Acquisition protocol (Hastedt and Luhmann 2018)

The bases and the ball prisms are handled with cotton gloves to avoid any disturbances, which could have an impact on the accuracy*. The magnetic coded targets and the measuring bars are placed around the object.

The museum having no suitable camera, a high-quality commercial model was chosen (see Figure 5-21).

The DSLR-Nikon D4 with a 35mm fixed objective lens was used by Schmik, a 50mm by Hastedt and a 4928 x 3280px sensor from the IAPG. The camera was equipped with a ring flash and a wireless transmitter to be able to transfer the pictures in real time to a computer.

159 Personal communication with the surveyor

160 Ebb is the tidal phase during which the tidal current is flowing seaward and flood is the tidal phase during which the tidal current is flowing inland http://www.coastalwiki.org/wiki/Definition_of_ebb_and_flood_(tide) (last visit 12.03.2023)

Figure 5-21: Heidi Hastedt - Photogrammetry acquisition on-going (Colson 2017)

The laptop was not only receiving the pictures, but also pre-processing the data. The parameters of the acquisition were set up beforehand by Hastedt in the software 3D Studio from AICON. These included the acquisition route, the camera positions, and the reference points (see Figure 5-21). Thanks to these ‘presets’, the software could indicate if the necessary amount of data has been collected during the acquisition (in green) or if more were needed (in red).
Each picture should include as many reference points as possible, where the furthest reference point should not be more than 20m away from the camera.

5.4.4 Data assessment

At this stage the goal was to be able to differentiate between the various types of displacement that the *Bremen Cog* was subjected to (see 4.1.1.2 Mathematical description of movement p 67). In order to achieve this, the data quality had to be ensured. Thus, the data from the coordinate system was assessed using the Monte Carlo simulation* (see 4.1.4.2 Evaluation p 78) and compared to real data coming from the laser tracker acquisition.
The deviation is characterized using RMS_{XYZ}* and the estimation is compared to the measured data. Here the difference between estimation and real data was very low, for each epoch (Schmik et al., 2018):

- Simulation=0.026mm and
- Measured=0.038mm.

The images have been processed altogether using bundle adjustment* (see 4.1.4.3 Processing p. 80).
The coordinate system and objects points were processed using congruence analyses (CON)* (see 4.1.4.4 Assessing p. 80) combined with F-distribution* by Schmik.

The test revealed that 95% of the points were reliable and with it the data set was consistent enough to be trusted for further analysis (Schmik et al., 2018). Later on the data was processed with T-distribution* by Hastedt, which when following the F-distribution makes sense for large data sets to increase the degree of freedom (Luhmann et al., 2020, p. 106) (Hastedt et al., 2019).
Additionally, the data was run through a signal-to-noise ratio* (SNR) test to assess the noise to ensure the level of accuracy* $q > 5$ (for technical details see 4.1.4.2 Evaluation p. 78).

5.4.5 First results

At the time of writing this thesis, the first results include the work of Schmik and Hastedt cited in the dissertation and conducted in 2017 and 2018.
It should be recalled that a displacement is not necessarily a deformation, but deformation always include displacement which makes identifying trends a challenge (see 4.1.4.4 Assessing p 80).
As described previously, strain* analyses play a central role in deformation analysis. The *Bremen Cog*'s data was divided into triangles, each having an orientation vector from the first acquisition (Epoch 0), and compared to the next (Epoch 0+x). At this stage, only the significant points are taking into account using the signal-to-noise* (SNR) to filter the dataset (see 4.1.4.2 Evaluation). After that, the vectors are compared using transformation theory based on dilatation (see 4.1.1.2.Mathematical description of movement) (see 7zFigure 5-22). During the first trials, the vectors remained lower than 1.3mm, indicating that the monitoring system was providing the requested output (Hastedt et al., 2019). The difference between Epoch 2 and Epoch 0 was under 1mm. The main changes seemed to occur on portside towards and in the bow area, overlapping with starboard side, although one area in the stern was also concerned (Schmik et al., 2018).
Looking at the data, it would show that the first half of portside tends to tilt further toward the outside of the ship and the first quarter of starboard side tends to follow it towards the inside of the ship. If this trend would be confirmed, it would mean that the ship will experience in the near or far future some tensions in the middle part, and if the rest of the wood stays still or cause some ruptures.
The protocol has been extended by Heidi Hastedt in 2020 and the monitoring conducted twice a year. However, the author is not involved in this process any longer since June 2019. The corresponding datasets had not been interpreted yet and remained unpublished at the time of writing this thesis[161].

[161] Personal communication with Heidi Hastedt – November 2022

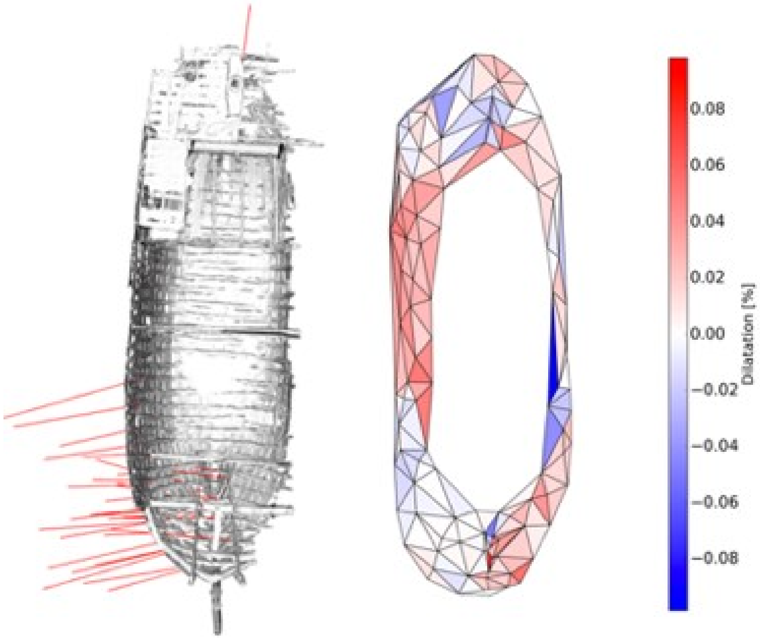

Figure 5-22: Strain analyses vectors dilatation Epoch 2 - Epoch 0 (Schmik 2017)

Although the ship had undergone some deformations, it is presently not possible to give a quantitative estimation. Nevertheless, photogrammetry* did clearly show its relevance in the context of spatial monitoring of the *Bremen Cog*.

5.5 Summary chapter 5

The discovery of a well-preserved medieval cargo ship is rare. In 1962, as the *Bremen Cog* was found by chance in the river Weser, close to Bremen, and it was a sensation. The ship both fascinated the public and all specialists, and rapidly lead the decision makers to finance a rescue excavation. Later on, the ship was reconstructed and conserved in the newly founded German Maritime Museum in Bremerhaven, only 70 km from where it was found. In May 2000, after 38 years, the *Bremen Cog* was presented to the public. Sadly, one year later the first deformations* were noticed. After opting for a 'correction' and 'reshape' of the hull, the project was put on hold in 2008, when Per Hoffmann retired (5.1 The *Bremen Cog*).

Although the ship was surveyed several times, nobody understood completely the origin and the scale of the deformation processes, which made impossible to determine what the ship needed.

In order to find out how the ship's geometry changes over time, the author proposed in 2014 the idea of a spatial monitoring (5.2 Aims).

The path towards the spatial monitoring was complex. First trials occurred supported by the European COST Action COSCH, testing several methodologies: structure-from-motion*, laser scanning* and total station* (5.3 Preliminary trials – COSCH (2014-2016)).

But it is only through the cooperation with the University of Applied Sciences, Oldenburg, Institute of Applied Photogrammetry and Geoinformatics, that the project reached the necessary scientific level. The cooperation with Prof. Thomas Luhmann and Heidi Hastedt provided the scientific expertise that the project was lacking before. Feasibility studies were conducted by Jurij Schmik in 2017 part of his master thesis, supervised by Hastedt, and data started to be collected and documented in a systematic manner. An acquisition protocol was proposed in 2018, and the first data sets were collected (5.4 Spatial monitoring 2016-2019).

At the time of writing this thesis, the project was assigned to the new conservator at the museum, and the author is not involved anymore since June 2019. A cooperation contract has been signed between the DSM and the IAPG in 2020 to continue to monitor of the *Bremen Cog* long-term. More targets were added to the ship and more acquisitions had been conducted. However, the data is still challenging and has not been assessed yet, which means no quantitative estimation can be given on deformations of the ship at this stage.

6 CONCLUSIONS

This thesis aimed to give an overview of the scope of problems that conservators and museums professionals face caring for archaeological wooden ships on display in museums and suggest some directions. This chapter summarises the notable facts gathered from comparable projects as presented in details under 4.3 Spatial monitoring of archaeological ships in museums (see 6.1), the lessons learned by the author throughout the case study of the *Bremen Cog* chapter 5 (see 6.2), and furthermore provides some recommendations (see 6.3), followed by a discussion (see 6.4), future perspectives (see 6.5) and final words (6.6).

6.1 Review on archaeological ships monitoring

6.1.1 Other initiatives

6.1.1.1 Measuring systems

At the time of writing this thesis only five initiatives are conducting spatial monitoring on archaeological ships in museums, all situated in Europe. However, in the past twenty years, many rescued ships have been documented and acquired three dimensionally using 3D technologies and of those a few examples should be mentioned: the *Newport Ship* (UK), the *Doel Cog* (Belgium), and the *Ijssel Cog* (the Netherlands), among many others. Some of them are at present still undergoing conservation treatments and will hopefully one day be presented in a museum. All ships that will need a spatial monitoring system.

According to a survey conducted in 2015, there are about 90 archaeological ships or boats on display in European museums (Crouzet and Meunier, 2016) (see Appendix A p. A-1). Based on this number, which is not exhaustive, it can be said that only 5% are under spatial monitoring currently.

In terms of methodology and technologies, the five mentioned initiatives (see 4.3 p. 85) reveal both similarities and differences. Two approaches stand out: either measuring single points using a total station* (TS), or multiple points using photogrammetry* measuring systems, see Table 6-1.

The first initiative was established in Stockholm at the *Vasa* Museum in 2000, making it a pioneer project once again. This also inspired all four other projects which were initiated about 15 years later.

In terms of staff, the spatial monitoring requirements vary from none (*Mary-Rose*) to two operators (*Vasa*) needed to conduct an acquisition. However, the larger difference rests with the time needed for each acquisition: from a few minutes (*Mary-Rose*) to 20 person-days[162] (*Vasa*).

Comparing the accuracy* was impossible, as the author could not gain access to the raw data, and such an assessment should ideally be done by an expert.

[162] 10 working days per operator, considering two operators

Ship	*Vasa*	*Mary-Rose*	*Arles-Rhône 3*	*Oseberg*	*Bremen Cog*
Start	2000	2014	2015	2016	2017
Type of technology	Total station	Total station	Total station	Photo-grammetry	Photo-grammetry
Recurrence of measurement	2x / year	3x / day	3x / year	4x / year	2x / year
Acquisition duration	120 person-hours	Minutes	8 person-hours	7 person-hours	3 person-hours
Object points	400	35	168	180	122
Number of operator (s)	2	0	2	1	1

Table 6-1: Overview of ship's spatial monitoring acquisitions

- Total station (laser-based)

The total station* (TS) acquisition requires installing fixed targets on the ship's hull by drilling holes into the original material. This ensures a high accuracy* but makes the system invasive and destructive.
On the warship *Vasa* there are 350 targets on the ship's hull and 50 inside (see Table 4-1: Overview of the monitoring setting from the *Vasa* (A. Colson) p. 91). Since the room is very dark, additional light is necessary, which is why a second operator is required. A single acquisition takes 10 working days, equivalent to 20 person-days considering the two operators, and is performed twice a year. Originally, the acquisitions were conducted by university students. However, to maintain the same level of quality, the museum staff took over at a later stage. This means that the personnel costs are high.
For the *Mary-Rose*, the system is completely automated, and 35 targets are acquired three times a day, without requiring any human intervention (see 4.3.3.3 p. 94). This is the only automated spatial monitoring and also the fastest acquisition.
As for the *Arles-Rhône 3* in France, the 168 points are measured within four hours with the help of two operators, equivalent to one person-day, three times a year. Reflective targets are not fixed onto the ship but in strategic locations within the area, in order to respect conservation ethics. This means that object points on the ship are recorded targetless, which reduces the accuracy* (see 4.3.4.3 p. 98).

- Photogrammetry (image-based)

The other two initiatives use image-based systems. Photogrammetry* is used on the Viking ship *Oseberg* (see 4.3.5.3 p. 102) and on the *Bremen Cog* (see 5.4.3 p. 133). Although the acquisition time is very different, the two systems both require one operator. Some reflective targets have been 'glued' onto the ship's hull with reversible adhesive.

In Oslo, the 180 targets are acquired in two separate acquisitions in a seven hours period, equivalent to one person-day, and conducted over night to avoid visitor traffic. In the future this spatial monitoring is planned to be executed four times a year.

In Bremerhaven, 20 reference points, more than 100 object points and about 400 coded targets are measured in about three hours, by one operator. The acquisition must consider the tides and plan to start one hour before slack tide, when water stands still.

- General comments

One important aspect must be noted: none of the spatial monitoring systems described here use laser scanning*.

	Laser-based	Image-based
Pros	♦ Motorized acquisition of repeated measurements ♦ Easy all-around measurement	♦ More flexibility for the operator when the room situation changes ♦ Images contain surface information ♦ Can be used for other purposes (visualisation and museum education) ♦ Acquisition time ♦ Accuracy
Cons	♦ Limited accuracy ♦ Acquisition time ♦ Equipment price ♦ Requires analysis with expert's software	♦ Light dependencies of the camera ♦ Requires analysis with expert's software

Table 6-2: Overview Pros and Contras Spatial Monitoring systems

When laser scanning was used, it was to gather additional data that was combined or fused with the 'main' data set, as in the case of the warship *Vasa*, *Mary-Rose* or *Oseberg*.

Although photogrammetry* or total station* do not necessarily require fixed targets, the only way to achieve the desired accuracy* and detect deformations* in a range of 1mm, is by installing targets on the object (see 4.1.2.2 Targeting p. 69). Table 6-2 provides an overview of the pros and cons of each approach from an end-user perspective. For an engineering overview, see the table 'State-of-the-art' by Heidi Hastedt (Hastedt and Luhmann, 2018).

6.1.1.2 Expertise involved

Planning and designing a spatial monitoring system is not trivial and the question of the necessary expertise is always central. In order to gain a general overview and to enable a comparison between the various projects, a list of people and functions of all the involved participants on each project has been established (see Table 6-3: Expert overview).

Ship	*Vasa*	*Mary-Rose*	*Arles-Rhône 3*	*Oseberg*	*Bremen Cog*
Coordinator (Name, profession, function)	- J. Jacobson, archaeologist, and head of collections unit - A. Ahlgreen, engineer - M. Sahlstedt, conservator - H. Thoren, archaeologist	- Prof. Dr. E. Schofield, material scientist, head of conservation and deputy CEO	- M.-L. Courboulès, conservator	- D. Hauer, conservator and Phd Fellow	- A. Colson, conservator, and PhD Fellow (until June 2019) - S. Wiedmann, conservator (since 2020)
Cooperation partner (Name and type)	- Prof. Dr. M. Horemuž, Royal Institute of Technology, Engineer and Head of Division of Geodesy and Satellite Positioning, University of Stockholm	------------	- Dr. D. Peloso, archaeologist, SME Ipso-Facto - V. Dumas, archaeologist, and surveyor, CNRS Centre Camille Jullian, University Aix-Marseille - H. Bernard-Maugiron, conservator, Arc Nucléart Laboratory	-------------	- Prof. Dr. T. Luhmann and - H. Hastedt, IAPG, Jade University of Applied Sciences, Oldenburg

Table 6-3: Expert overview

As depicted in the table many different collaboration models exist, but it should be noted that three out of five initiatives opted for a university cooperation.

In Sweden, Milan Horemuž has a yearly allowance of his services. This work includes the data processing and adding the latest data sets into the collection, as well as the visualisation on the platform he programmed in MATLAB. The final version is handed over to the Museum, where Jacob Jacobson, but moreover Andres Ahlgreen, Malin Mahlstedt, and Håkan Thoren are using the data.

In England, additional institutions and experts are called in depending on the project's needs, sometimes including PhD Fellows enrolled in different universities. The spatial monitoring is coordinated by Prof. Dr. Eleanor Schofield.

In France, the Arles Antique Museum has a maintenance contract with the conservation laboratory Arc Nucléart, whose annual visits are invoiced, as well as the staff from Ipso-Facto. The University is participating at a research level and therefore does not receive any financial compensation. At the museum, Marie-Laure Courboulès, a mosaic conservator, coordinates the spatial monitoring of the *Arles-Rhône 3* on top of her regular tasks.

For the *Oseberg*, in Norway, no partnership exists except the exchange with the working group 'Monitoring of Preserved Ships' (MoPS) (see 6.1.3). The only person in charge is David Hauer, conservator, working on the project as part of his doctoral thesis and being employed on a short-term contract.

In Bremerhaven, the DSM has an official scientific cooperation partnership with the IAPG.

6.1.2 Bremen Cog

6.1.2.1 Measuring systems

As described in chapter 5 CASE STUDY, several technologies were applied to the *Bremen Cog* over the years. The following remarks about measuring systems are based on the author's perspective only, and therefore approached from the perspective of an end-user as opposed to a strictly engineering viewpoint.

Although, the reasons for choosing photogrammetry* are described in paragraph 5.3.6 p. 127 and 5.4.1 p. 128, the number of acquisitions and the duration is stated in Table 6-4. Each acquisition generated a level of knowledge and understanding which in turn led to the actual spatial monitoring protocol. Which means, that no trial can be considered as a waste of time.

Technologies	Number of acquisitions	Dates	Acquisition duration
Structure-from-Motion	4	2014, 2015, 2016	2 hours
Terrestrial laser scanning	1	2014	3 days
Total station	3	2015, 2016	16 hours
Photogrammetry	5	2017, 2018	4 hours
Extended Photogrammetry[163]	4	2020, 2021, 2022	3-4 hours

Table 6-4: Comparison of technologies used on the Bremen Cog

In the end, photogrammetry* was the best fit. Additionally, since operating a camera is an essential skill for every museum professional (conservators and curators), we reasoned that in the future the acquisition could be performed by museum staff members. The chart summarises the advantages and disadvantages of each technology, as applied during the case study, see in Table 6-5. Green indicates image-based technologies and blue laser-based technologies.

	Structure-from-Motion	Terrestrial laser scanning	Total station	Photogrammetry
Pros	- Flexibility - Visualisation	- Easy acquisition of point clouds	- Visualisation - Profile	- Flexibility - Accuracy - Acquisition duration
Contras	- Accuracy - Light dependency	- Limited accuracy - Acquisition duration	- Invasive - Acquisition duration	- Light dependency

Table 6-5: Overview Pros and Contras Spatial Monitoring Bremen Cog

The *Bremen Cog* was surveyed and acquired three-dimensionally many times. The following graphic plots all acquisitions in a timeline (see Table 6-6). It shows that spatial monitoring is a long-term issue, where several generations of professionals participated, and during which technology is evolving.

[163] High accuracy photogrammetry based on laser tracker network

The first photogrammetry* survey focussed on documentation and intended for archaeologists on the ship construction. The second one, aimed to compare the data gathered over more than twenty years to reveal geometrical changes.

Date	Technology	Type of acquisition
1981	Photogrammetry (analogue)	documentation
2003	Photogrammetry (digital)	data comparison
2009	Laser scanning	planning support
2014	Structure-from-Motion 1	monitoring
2014	Laser scanning	monitoring
2015	Structure-from-Motion 2	monitoring
2015	Total station Theodolite 1	monitoring
2016	Structure-from-Motion 3	monitoring
2016	Total station Theodolite 2	monitoring
2016	Total station Theodolite 3	monitoring
2017	Photogrammetry 1	monitoring
2017	Photogrammetry 2	monitoring
2017	Photogrammetry 3	monitoring
2017	Photogrammetry 4	monitoring
2018	Photogrammetry 5	monitoring
2020	Photogrammetry 6	monitoring

Table 6-6: Timeline of 3D acquisition of the Bremen Cog

The laser scan from 2009 was focusing on the inner ship, in order to plan the manufacturing of the new (never built) support. Since 2014, the *Bremen Cog* has been three dimensionally acquired for spatial monitoring.

6.1.2.2 Equipment

As a matter of fact, the budget defines very often how an object will be measured. To give a global and transparent overview of the financial investment necessary to conduct a spatial monitoring, all the equipment used has been listed (see Table 6-7) [164]. Some items were purchased by the DSM and others were provided by the IAPG, identified in the table through different colours.

[164] Please note that all equipment acquired after June 2019 is not listed here, since the author left the museum after that date

Over time the idea was to purchase all necessary items so that the museum staff could perform the acquisition on their own, except for the software, since the data processing would continue to be done by the engineers of the IAPG.
At the beginning of the project a digital reflex camera was owned by the museum and did not need to be purchased. Unfortunately, the situation changed over the course of the project[165]. Following the suggestion of Heidi Hastedt, the museum only bought ten adapters (see item #5), when in fact 20 were needed in order to reduce possible mistakes while moving them from one reference point to the next. Since at that time each adapter cost 40€, it was decided to start with a lower amount. On the other hand, all the hemispheric targets, either for the laser tracker or for the photogrammetry (see item #6 and #7), were provided by the IAPG and brought from Oldenburg for each acquisition.

#	Purpose	Equipment	Price (€)	Numbers	Total (€)
1	Camera	Nikon D4	1,500	1	1,500
2	Light	Ring flash	150	1	150
3	Data transfer	Wireless transmitter	300	1	300
4	Coordinate system	Measuring bolts	2.5	20	50
5	Coordinate system	Measuring adapters	40	10	400
6	Coordinate system	Magnetic targets laser tracker	150	10	1,500
7	Coordinate system	Magnetic targets 1,5” hemisphere 20mm	550	14	7,700
8	Object points	Reflective stickers for a set	200[1]	200	200
9	Object points	Coded targets 14bit Ø1=10mm Nr. 2500	1,800[1]	400	1,800
10	Processing	Software AICON 3D Studio	2,500	1	2,500
				Total investment	16,100 €

Table 6-7: Overview of used equipment and prices
(owned by the museum; provided by the IAPG; [1] Price for a full set)

[165] The purchase of a new camera was planned, but the current situation is unknown

This means that the museum carried out the first measurements with an investment of only 450€, and the investment was spread over several years. All indicated prices in the table are based on real prices from suppliers. The overall project budget does not include transport costs and working hours by Heidi Hastedt (NOTE: this information cannot be made public for confidentiality reasons). Therefore, the total of 16,100€ only includes the equipment. All mentioned prices were collected between 2016 and 2019 by the author.

6.1.2.3 Expertise involved

As already mentioned, several times in this work, the initiator of the spatial monitoring on the *Bremen Cog* is the author, a conservator of archaeological objects. Initially she was employed in her capacity as conservator (2013-2015) and later as a PhD Fellow (2016-2019). This implies that the coordinator for the project was not a permanent staff member. In 2020, a conservator[166] was appointed at the DSM and took over the responsibility for the spatial monitoring of the *Bremen Cog*[167].

Since the museum did not have the geodetic expertise, it became clear around 2016 that additional support and expertise were needed, and a collaboration with the Jade University of Applied Sciences was initiated (see 5.4.1.1 p. 128). Although the two parties agreed on most aspects of the partnership, the official contract was finalised and signed in 2020[168]. The personal and professional involvement of Professor Thomas Luhmann and Heidi Hastedt have had an immense impact on the success of this project. For a comparison of expertise with the other four initiatives of spatial monitoring of ships see Table 6-3 p. 142. The cooperation contract also addresses the issue of publication and intellectual property.

6.1.3 European working group MoPS

Researching on archaeological ships in museums and how to monitor their geometrical changes made us realise how limited the number of existing initiatives was. After contacting all four institutions involved in monitoring projects, as well as others that were conserving ships, the need for sharing knowledge and experience became obvious. Some of the researchers contacted were aware of the existence of the others, but not all. After sounding out everyone individually, the author suggested a common meeting.

[166] Silke Wiedmann

[167] Permanently employed since 2022

[168] PhD-Fellowhip was already over

The first meeting was organised in June 2017 in Bremerhaven and gathered experts from nine European countries, 17 research institutes, and from several disciplines including: structural engineering, geoinformation, geodesy, material science, archaeology, ship building, art history, and conservation-restoration. All of them were or are still involved in one or several of the five initiatives of spatial monitoring of archaeological ships in museums presented in chapter 4 (see 4.3 p. 85). It was agreed upon to build an informal working group and to organise annual meetings. The author was appointed as coordinator and David Hauer (Oslo University) as co-coordinator. The group agreed on the name: "Monitoring of Preserved Ships" (MoPS). The aim was to exchange experiences on a very practical level, discussing about what worked and what did not, and eventually to apply for funding as a consortium. On top of this, the group members supported each other in communicating with their boards of directors and have consequently gained more awareness and legitimacy to spatial monitoring in each institution – a clear effect of this synergy.

A similar initiative was started in 2015 in France, called GEISER (Groupe d'Étude et d'Information pour le Suivi des Épaves Restaurées), led by Marine Crouzet and Laure Meunier supported by their laboratory Arc Nucléart, Grenoble. Unfortunately, this group has been inactive since 2017[169].

The need for a broad expertise and know-how with regards to archaeological ships in museums has turned out to be of high scientific relevance when several members of the MoPS group[170] were, in May 2019, invited by the Smithsonian Institution in Washington DC (USA) to participate to a scientific expert group. The American History Museum organised a scientific meeting and gathered experts from Europe and the United-States to discuss the future conservation and exhibition of the gunboat *Philadelphia*, built in 1776, which had been on display in the museum since the 1960's. The gunboat (oak wood, about 16m in length) was salvaged in 1935 after 159 years underwater and is the oldest known surviving vessel in North America remaining from the colonial period (Fix, 2010).

6.2 Lessons learned

Throughout the course of this research, aspects were noted and are presented in this section to help others to avoid making certain mistakes or simply not to waste precious time. This is based on the author's experience and observations made at the German Maritime Museum (Bremerhaven) as well as the other four museums that are conducting spatial monitoring on archaeological ships.

[169] The group stopped to be active in 2017 as Marine Crouzet left Arc Nucléart Laboratory

[170] Including the author

Therefore, while this information could help other professionals in similar situations, and is worth sharing, it should nevertheless be understood as part of a specific context.

6.2.1 Initiate spatial monitoring

After the experts' meetings at the DSM in November 2013, the need for a new support for the *Bremen Cog* was indisputable. The remaining questions were: What does the ship require and how can we be sure that we design an adequate support?

One thing was certain, building a new support would involve high costs. When a high amount of resources are invested in an artefact the involved parties need to be certain that the right decisions are taken. Clearly this was a unique opportunity for the ship, and accordingly it called for the utmost care in planning.

Conscious of the issues at stake, the work conducted in Bremerhaven crystallised around the long-term objective of a new support. The first step was to acquire the necessary knowledge of the ship itself and her mechanical behaviour.

Initiating a spatial monitoring campaign requires individual conviction and persistence. Conservators need to convince their supervisors (often the directors), and the relevance of spatial monitoring should be justified based on the object's state, and also integrated into the current conservation debate (see 2.2 The on-going preventive conservation debate p. 41). It is always easier to argue that taking care of a large artefact 'in time' is without doubt more cost efficient than waiting for it to fall apart and only then leaping into action.

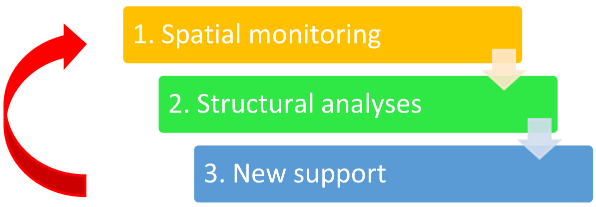

Figure 6-1: Bremen Cog - General direction

For the *Bremen Cog*, we needed to collect information on the ship's conservation state and understand the deformation* to be able to plan a new support system. The journey to reach our objectives was divided into three stages: 1) spatial monitoring, when the geometrical information is gathered and compared over time; 2) structural analyses, when collected data is interpreted and critical areas identified; 3) a new support system, when thanks to all the information collected the new support system can be designed and implemented (see Figure 6-1). At a later time, the support should also be assessed using same spatial monitoring system.

Initiating the spatial monitoring meant discovering more information about other initiatives, for example by looking into the different technologies available and starting to contact other researchers in the field; this stage took the author six months.
Making the initial assessment of the situation should not be underestimated as it often takes much more time than one initially imagines. For details about the spatial monitoring workflow see 6.3.1 Recommended workflow.

6.2.2 Speak '3D measuring'

As mentioned in 2.4.3 Conservators' education p. 50, notions of geodesy or surveying are not part of the classical curriculum, which means that conservators start with a significant lack of knowledge. Since museums very rarely employ engineers or surveyors and conservators have little background in these fields, the only two options are: 1) find information alone and 2) get some help. Getting into a new field of expertise is challenging and accessing a few chosen publications can help to get off to a good start. Some new publications have been published over the course of this research, showing how dynamic the topic current is.
To earn a spot at the table, one needs to know enough of both the partner's mindset and their discipline to be able to start a conversation. Conservators are not yet used to work together with experts in geodetic measuring systems and a common ground needs to be established. The 'new' discipline does not need to be mastered; it is enough when the basic knowledge and vocabulary is acquired, then a dialogue can start on a completely different level. Having 'previous knowledge' will be a big help and this took the author about 1.5 years and long conversations with colleagues from the COSCH group[171], to acquire. Therefore, by the time of starting this PhD the first notions were already understood. Understanding geodetic measuring systems is crucial; it makes things more efficient and avoids misunderstanding. The most relevant notions required to actively participate in the design of a spatial monitoring system can be found under 4.1 Measuring and monitoring three dimensions: fundamentals p. 65.
A way to be more aware of the differences between disciplines is to use tools from cross-cultural communication, for example the model of culture and behaviour called the 'Iceberg Analogy of Culture' by Gary R. Weaver (Weaver, 1986). Based on the idea that some individuals have more difficulties adapting to a new environment, several specialists have spoken about physical and emotional discomfort, which in some cases leads to *"anxiety resulting from losing all our familiar signs and symbols of social intercourse"*. Beyond this 'culture shock', the point is to look into how individuals adapt and adjust to new processes and develop coping strategies.

[171] Cost Action TD1201 "Colour and Space in Cultural Heritage"

Although this model was used in a cross-cultural business context, it can also be used in a cross-disciplinary one. When behaviour and beliefs belong to external culture, they are 'above the waterline'. Internal culture, however, is underwater, and this is where the culture *"clash occurs (...) where values and thought patterns conflict"* (see
Figure 6-2). On the assumption that a 'discipline' can be understood as a 'culture', a parallel can be drawn. This model helps us realise how complex cross-disciplinary projects can be on a personal level, so that after the first 'culture shock' only communication can solve the unspoken issues and then thus allow the actual scientific cooperation to start.

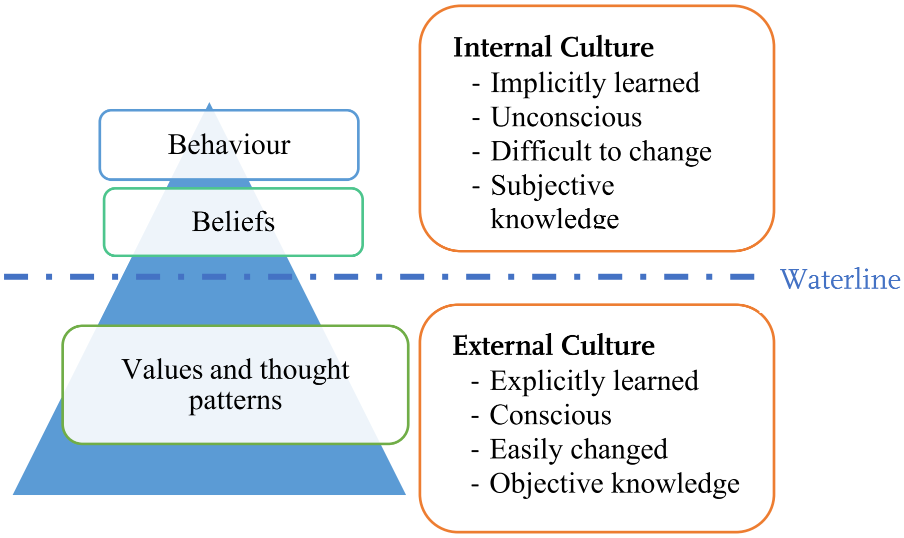

Figure 6-2: Iceberg Analogy of Culture (after Weaver, 1986)

This model helps us realise how complex cross-disciplinary projects can be on a personal level, so that after the first 'culture shock' only communication can solve the unspoken issues and then thus allow the actual scientific cooperation to start.

6.2.3 Standard 'recipe'

Another important aspect learned is that exactly like in conservation there is no standard 'recipe' that can be applied to all cases on all objects, and there is no standard geodetic measuring system that can be applied to conduct all spatial monitoring. Every case is unique and within the process of designing a spatial monitoring, context, resources, and goals should always be assessed and carefully taken into account.

It is not far-fetched to say that the mindset of geodesy or metrology has a lot in common with conservation-restoration of cultural heritage (see 4.1.1 p. 65 and 4.1.1.1 p. 66).

In the case of the *Bremen Cog*, the spatial monitoring is the result of many hours of discussion with all involved participants, followed by months of work, all which together had led to the final protocol (Hastedt and Luhmann, 2018).

All five spatial monitoring initiatives had some support, either through formal partnerships or informal discussions, where conservators could exchange knowledge with geodetic measuring experts. None of them is the result of a single person working all alone, hence, the emphasis on the need to share information and form a network.

6.3 General recommendations

6.3.1 Recommended workflow

To facilitate a good start for a spatial monitoring project, beginning in a structured manner is the most important requirement. It is crucial to make a list of: a) the problems and b) the resources available before entering the planning phase. Most of the time certain resources can be made available only for a limited time period, corresponding to research funding, and stop after three or five years. Therefore, knowing what is available in 'normal' times is fundamental to calibrate the spatial monitoring accordingly, and calculate the institute resource and staff budget wisely. As a matter of fact spatial monitoring is a long-term task. In the case of the *Bremen Cog*, we had 10 to 20 years in mind.

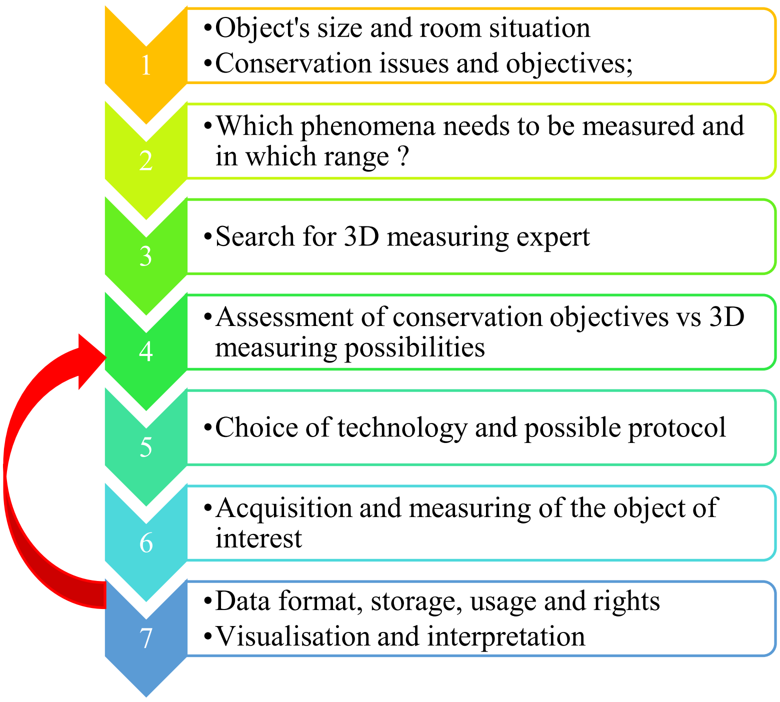

Figure 6-3: Proposed workflow for spatial monitoring for set-up

Inspired by the design procedure of structural health monitoring (see Figure 4-1 p. 66) the following workflow can be proposed, see Figure 6-3. The seven steps should be understood as milestones in the process of setting up the monitoring, and each one includes several tasks.

Step 1: is dedicated to the gathering a catalogue of information required to comprehend the object. Every document such as condition reports, pictures, intervention history, and information on the archaeological or historical relevance must be collected. The conservation issues should also be stated, and the objectives justified. In conclusion, all constraints should be listed, such as the display situation (indoor or outdoor), e.g. through the architectural plans, museum opening hours, the possibility to work at night, or the lighting situation for indoors and the allocated staff (permanent or not).

Step 2: is about pointing out what has to be done, it means listing the type of threat(s) to the object. If possible, it should also be stated in which range the phenomena should be measured.

Step 3: At the latest during step 3, the conservators should try to fill in their knowledge gaps and should have found the right cooperation partners (see 6.3.2.1). Here, it should be mentioned that steps 1 to 3 can take up to several months and be considered as the project set-up. These three steps are actually conducted more or less simultaneously.

During **step 4:** the spatial monitoring really starts and becomes concrete. At this stage, the discussion between conservators and experts focused on the objectives and the feasibility. There technological options will be discussed, and objectives adjusted. A 'swinging' effect can be expected at this point, adjusting between expectations and reality until the balance is found. Compromises will have to be arbitrated. Very often, the available budget and other resources dictate which option will be chosen. For this reason, steps 1 and 2 are vital.

During **step 5:** tests of the technology(ies) are conducted, and the possible protocol(s) should slowly take shape. Based on the initial results and after discussion, the final choice of a technology and the appropriate protocol can be made.

Step 6: the acquisition or the action of measuring the object of interest with or conducted by or with the expert.

Step 7: is focused on the 'small' details that are often forgotten, i.e., data management. Here, it is relevant to discuss the long-term data storage (format, usage, rights) as well as the responsibilities of each project partner. The final element is the visualisation of the results in a form that can be useful to the conservator and/or other museum staff. If the system doesn't provide the expected outcomes, the process should be started again from step 4 to be improved and optimized.

None of the tasks related to each step are not negligible especially in the case where one has never undertaken such a project. Every step should be approached cautiously and consciously. If necessary the process has to be repeated back to step 4 (see red arrow on the illustration).

6.3.2 Necessary infrastructure

6.3.2.1 Expertise

It is hardly possible for a conservator to outline a spatial monitoring protocol completely alone. In fact, bringing an archaeological ship from the excavation to the museum involves many different disciplines and professions. The workflow of archaeological ship projects has been described in Chapter 1 (see 1.1.3 p. 27).

Based on the five initiatives described in chapter 4 (See 4.3 p. 85) and on other similar projects in ship archaeology, a generalised overview can be extrapolated (see Table 6-8).

Seven fields have been identified as expertise required to conduct such projects efficiently: 1) Conservation/Restoration; 2) Ship Archaeology; 3) Geodesy/Surveying; 4) Structural Engineering; 5) Ship building; 6) Conservation Science; 7) Museology/Museum design. This project structure is an original work by the author. The diagram was developed while trying to list all the experts involved on the *Bremen Cog* and the warship *Vasa* in order to objectively compare the resources invested on each ship. The decision was taken to disregard budgets and personnel, since every project is endowed and financed differently, and yet to remain practical. The question was: which requirements are absolutely essential?

The project phase **1)**, **2)** and **3)** will not be described, but are indicated in the diagram to help to understand the whole. The spatial monitoring is ideally taking place alongside with planning both the museum presentation and the long-term preservation of the ship. But the best would be to track geometrical changes from the excavation to the museum presentation.

This means that the needed know-how can be found in all phases, but in our case under **4) Presentation** and **5) Preservation**.

It should be noted that **Presentation** is the most challenging phase, when all experts should sit at the table. It is often considered as the last step and frequently underestimated. However, everything is at stake at this moment. Decades of conservation treatments, 19 years for the *Bremen Cog*, can be ruined or rendered pointless, if the support and the presentation concept is not designed properly and later monitored carefully. When some problems appear later on, phase **4)** and **5)** need to be studied again and in a worst-case scenario more conservation is called for, asking to revert to phase **3)**.

Looking at Table 6-8, the necessary expertise will be either already existing within the institution or needs to be acquired. There are two options: 1) procure the expertise commercially and pay a company; or 2) 'borrow' some help through a partnership with a research institute that will also benefit from the project. As we can see in Table 6-3 p. 142 and 6.1.2.3 p. 147, all the different models coexist and have their own advantages and disadvantages.

However, working with research institutes usually offers the opportunity to benefit from students' support through bachelor or master's thesis, and benefit from the experience of highly qualified specialists and academic staff.

		PROJECT PHASES				
		1) Excava-tion	2) Reconstruc-tion	3) Conser-vation	4) Presen-tation	5) Preser-vation
EXPERTISE	Conservation /Restoration	■	■	■	■	■
	Ship Archaeology	■	■		■	
	Geodesy/ Surveying	■	■	■	■	■
	Structural Engineering		■		■	
	Ship building		■		■	
	Conservation Science			■	■	
	Museology				■	

Table 6-8: Required expertise and know-how - A. Colson (2021)

In terms of staff, no permanent staff members were assigned for the spatial monitoring of the *Oseberg* and the *Bremen Cog*. At the DSM this fact has jeopardized the knowledge transfer and with it, to a certain extent, the success of the spatial monitoring.

6.3.2.2 Equipment

A geodetic measuring system cannot be established in a museum without close collaboration with the IT department: technical infrastructure is absolutely essential. Hardware, for example a sufficiently powerful computer, as well as the software requirements needs to be discussed with the IT manager, as well as the issue of the volume of data and the formats produced by the spatial monitoring and its subsequent storage.

Considering that museums are currently investing efforts into digitisation (see 2.1 Digitisation of museum collections p. 37) and hence in this type of infrastructure, some equipment might already be at hand. For software, depending on whether the data processing must be conducted by the museum, most software producers offer much lower prices for non-commercial users, such as universities or research institutes. The use of equipment will then have to be coordinated within the museum, which can sometimes be challenging. Nevertheless, the fact that museums focus on digitisation offers an opportunity to establish the necessary technical infrastructure.

Here no specific geodetic measuring equipment can be recommended, but it can be said that equipment can be borrowed from research institutes without having to be purchased. Some producers may agree to lend equipment to conduct tests, if they can then present the results or use them for their public relations.

6.3.3 Useful readings

The following references have been selected as compulsory reading. For those without pre-existing knowledge about 3D technologies, it could be helpful to start with *"3D Recording, Documentation and Management of Cultural Heritage"* by Stylianidis and Remondino (Stylianidis and Remondino, 2016) and *"3D Laser Scanning for Heritage – Advice and guidance to users on laser scanning in Archaeology and Architecture"* published by Historic England (Broardman and Bryan, 2018).
For more advanced knowledge focusing on spatial monitoring *"The Metrology Handbook"* by Bucher (Bucher, 2012c), *"Handbook of Technical Diagnostics – Fundamentals and Application to Structures and Systems"* by Czichos are very useful. Some German references had no English equivalent but were very central in understanding geodetic measuring systems and their applications such as: *"Ingenieurgeodäsie – Handbuch der Geodäsie"* by Schwarz and *"Auswertung geodätischer Überwachungsmessungen"* by Heunecke and his colleagues. To learn about image-based measuring systems and Photogrammetry, two books should be looked into *"Close-Range Photogrammetry and 3D Imaging"* by Luhmann and his colleagues (Luhmann et al., 2020), as well as *"Photogrammetry - Geometry from Images and Laser Scans"* by Kraus (Kraus, 2007), both books have a German version.

6.4 Discussion

In order to be self-critical and take some distance with one owns dissertation, the research questions and aims will be reviewed and answered shortly in this section.

6.4.1 Answering research questions and aims

<u>Questions</u>

1) How could deformation be monitored on archaeological ships over time and how geodetic measuring systems are suitable for this purpose?

Geometrical changes can be monitored using laser-based or image-based geodetic measuring systems, but such a monitoring need to be planned methodically together with professionals from the field of geodesy or metrology.

The requirement was defined by the author to detect about 1mm of movements, the set-up had very high standards. Geodetic measuring systems were used in industrial context to provide the similar information, for example spatial monitoring of bridges, it only needed to be adapted to cultural heritage.
This question is answered in 4.2 Spatial monitoring in moveable cultural heritage p. 82 as well as 6.1.1.1 Measuring systems p. 139 and Table 6-1 p. 140.

2) Could spatial monitoring be part of preventive conservation measures, as climate monitoring already is?

Since the aim of the conservation practice is to prioritise preventive measures, spatial monitoring supports this approach and provides data to optimize the long-term preservation of large-scale museum artefacts (see 1.2.2 Preventive conservation p. 31 and 2.2 The on-going preventive conservation debate p. 41). However, becoming a standard will require more knowledge transfer in the conservation-restoration community.

3) What is needed in museums to enable conservators to integrate geodetic measuring systems into their workflow?

Expertise and equipment are the central issues here. Conservators need to establish contact outside the museum world into engineering to get the necessary support, since this expertise is rarely at hand among museum staff. All the details can be found in 6.3.2 Necessary infrastructure p. 154.

4) Can we adjust standard climate values based on tangible facts?

We surely can and should adjust standard climate values, only if tangible facts are assessed and interpreted. The information recovered through spatial monitoring helps to adjust climate values. For the example of the *Vasa*, a new air conditioning system was purchased after analysing the deformations thanks to spatial monitoring (see 4.3.2.4 p. 91). But such approaches should be more implemented into museum infrastructure and added to an overall conservation goal.

Aims

1) Investigate geodetic measuring systems to monitor archaeological ships

This investigation has been done on two levels: 1) looking at what is currently done in the field, presented in section 4.2 and 4.3; 2) through the case study on the *Bremen Cog*, chapter 5. The different tests conducted on the *Bremen Cog*, whereas during the COSCH project or later on through the cooperation with the IAPG, the acquisition methodologies of total station*, SfM*, laser-scanning* and photogrammetry* were investigated (see 5.3 p. 121 and 5.4 p. 128).

2) Prove the relevance of spatial monitoring in preventive conservation

Based on the definition (see 1.2.2 in the terminology section p. 31) and on the brief overview on the current debate in preventive conservation (see 2.2 p. 41), it can be said that condition assessment is very important for museum professionals. Spatial monitoring contributes to achieve this goal and is therefore a relevant tool. However, the data interpretation is very complex and in the case of the *Bremen Cog*, the process is still on-going.

3) Embed geodetic measuring systems in conservation-restoration practice

While writing this dissertation, a lot of similarities between the mind-set of the two fields were identified. However, considering the lack of basic knowledge of most conservators in the field of geodetic measuring, its full integration will most probably take a certain amount of time.

4) Build a connecting bridge between geodetic measuring systems and conservation

Although this bridge was built over the course of this research and is a main achievement of this project, it is difficult to assume, that it can be generalized or even simply expected from all conservators. Even if some have natural affinity for engineering, it cannot be the case of all.

6.4.2 Scientific contribution

A list of the main scientific contributions of this research will be stated here:

- Overview of the conservation history of the *Bremen Cog* (in this monograph and in an article (Colson, 2021).
- The use of the term 'spatial monitoring' in the field of conservation-restoration for the first time.
- The link between spatial monitoring and preventive conservation for the first time in the field of object conservation, which could extend the precision of condition assessments.
- Building up a network of professionals at European level on this topic (Monitoring of Preserved Ships).
- Showing the importance of a post-conservation assessment tool and long-term preservation issues of archaeological wooden ships (Session at the ICOM-CC WOAM meeting 2019 in Portsmouth) (Colson et al., 2022a) (Colson et al., 2022b) (Hauer et al., 2022)
- First overview of necessary expertise to conduct a project on bringing archaeological ships from excavations to museums.

6.5 Future Perspectives

6.5.1 Bremen Cog

At the time of writing this thesis (2021) the DSM and the IAPG have signed a partnership and the spatial monitoring is being performed every six months by Heidi Hastedt. The idea to train a museum staff member has been abandoned, since the staff capacity is limited. For now, the collected data still needs to be interpreted and analysed to identify any trends and deformation* patterns. It appears that this stage was more complex than anticipated. Currently no recommendations can be drawn from a conservator perspective because the spatial monitoring did not deliver the necessary information to do so. If the results are not interpreted, and a clear statement of the situation is not available, the work of the conservator is on hold.

The next step would be to conduct a structural study and to design a new support system, but this can only be conducted when the information coming from the spatial monitoring is consistent. It seems that the museum has not initiated any follow-up projects dealing with these aspects. Considering the time and effort invested into the spatial monitoring it would be a pity not to continue and built on the expertise accumulated over the past few years. However, the museum has had to cope with a major dramatic event: the fire of the *Seute Deern* in February 2019. The wooden three-masted barque was considered as the flagship of the city and was followed by her sinking in September 2019 in the museum harbour[172]. Secondly, the new 'research storage building' was built during this period, opening in August 2020[173].

6.5.2 Capacity building

This research has shown that the expertise required to design a spatial monitoring is often not available in museums and thus needs to be acquired from outside the institution. Conservators need to be supported by other professionals and must complement their lack of knowledge in the field of geodetic measuring systems. This could be accomplished on two levels: 1) introduce structural engineering and geodetic measuring systems in the conservation curricula; 2) and build up lifelong training possibilities provided by higher education institutions for conservators already active in the profession.

[172] https://www.butenunbinnen.de/nachrichten/seute-deern-bremerhaven-geschichte-abgewrackt-100.html (last visit 12.03.2023)

[173] https://www.dsm.museum/pressebereich/dsm-feiert-richtfest-des-neuen-forschungsdepots (last visit 12.03.2023)

At the time of writing this thesis, the situation in Germany is evolving and the conservation program on archaeological objects at the HTW-Berlin University of Applied Sciences offers one module on 3D technologies and the conservation program at the ABK-State Art Academy in Stuttgart is also introducing this topic.

On the other hand, while the hyper-specialization of conservation professionals is often discussed and seen as both a blessing and a curse, it should never stand in the way of protecting the objects (Ashley-Smith, 2018).

6.5.3 Further work

The interest in spatial monitoring in conservation has risen over the course of this research and the same approach could be adapted to other objects, especially to those of similarly large scale. The Hamburger Bahnhof Museum in Berlin has expressed their interest in monitoring the geometrical changes of the famous artwork by Joseph Beuys called *Unschlitt/ Tallow* (1977).

Concerning archaeological wooden ships, the long-term preservation costs should be taken into account when a ship is salvaged, conserved and presented, including the on-site staff required to care for them. Other archaeological ships on display in Europe could benefit from the spatial monitoring as well. For instance, the recently salvaged medieval vessel *Tallinn Cog* on display at the Estonian Maritime Museum, which was slow dried and deliberately NOT conserved (Ehanti et al., 2021). The experiment was highly criticized by specialists, and a spatial monitoring would have been able to show objectively if it the results were satisfactory or not.

In Washington DC, the Gunboat *Philadelphia* might be conserved in the coming years and there could be an opportunity to establish a spatial monitoring in order to develop a tailor-made conservation solution.

The interpretation of the collected data is very challenging for all spatial monitoring projects and its complexity should not be underestimated. This should be the subject of future research. Spatial monitoring should also be adapted and implemented over the whole conservation process, which means before and during treatment.

6.6 Final words

The doctoral research has focused on accompanying the set-up of a spatial monitoring protocol, moreover, defining the goals and ensure conservation ethics together with experts in geodetic measuring systems. Systemic issues must be solved beforehand, even though the technology and the mindset proved to be valid, obstacles that slowed down the process and could not be overcome within the time frame of a PhD Fellowship. However, it could be shown that no assessment tool was existing to objectively evaluate the results and the success of conservation treatments of archaeological wood, neither to maintain a stable object condition procedure over long-term. The case study together with the review on existing initiatives on spatial monitoring of archaeological wooden ships in museums, make this research an unprecedented scientific innovation for the field of conservation.

Geodetic measuring systems are not part of conservators' curricula, and the knowledge gap is large. Focusing on the basic knowledge aims to have a constructive dialogue with the project partners and allow conservators to take part in decision making, is essential. However, a multidisciplinary cooperation can only occur when everyone is committed.

Actual issues concerning digitisation of museum collections, current preventive conservation debate, sustainability in museums, and the role of conservators, offer a key to build up on and hopefully to integrate spatial monitoring to common practices. Being a conservator does not mean to always being able to make recommendations, which can be frustrating, but we need to continue to constructively collaborate with other disciplines and to push boundaries.

7 AUTHOR'S CONTRIBUTIONS

Peer-reviewed

2017 Colson, A. "Digital Documentation of ships in Cultural Heritage: a European Review" in Proceedings of the *26th International Committee for Documentation of Cultural Heritage (CIPA)*, Ottawa, Canada. doi:10.5194/isprs-archives-XLII-2-W5-129-2017

2018 Hess, M., Colson, A., Hindmarch, J. "Capacity building and knowledge exchange of digital technologies in Cultural Heritage Institutions" in 70 ICOM Museum International.

2019 Hastedt, H., Luhmann, T., Colson, A. "Large volume photogrammetric deformation monitoring of the Bremen Cog" in Proceedings of the *4th joint International Symposium on Deformation Monitoring* (JISDM), Athens, May 2019.

2021 Colson, A. "The Bremen Cog: Conservation History" in *Maritime Archaeological Periodical (TINA)*, Special Issue: Shipwreck Conservation, 14, p. 176-191, Istanbul, Turkey.

2022 Hauer, D., Colson, A., Hastedt, H., Gamstedt, K. "Monitoring structural change of large, complex archaeological wooden objects – Application of fixed target photogrammetry" in Proceedings of the *14th Meeting of the ICOM-CC - Wet Organic and Archaeological Material Group*, Portsmouth, May 2019. https://www.icom-cc-publications-online.org/4654/Monitoring-Structural-Change-of-Large-Complex-Archaeological-Wooden-Objects---Application-of-Fixed-Target-Photogrammetry

2022 Colson, A., Hastedt, H., Luhmann, T., Hess, M. "The role of conservators in the implementation of surveying techniques – reflections on the Bremen Cog monitoring project" in Proceedings of the *14th Meeting of the ICOM-CC - Wet Organic and Archaeological Material Group*, Portsmouth, May 2019. https://www.icom-cc-publications-online.org/4653/The-Role-of-Conservators-in-the-Implementation-of-Surveying-Techniques---Reflections-on-the-Bremen-Cog-Monitoring-Project

2022 Colson, A., Hauer, D., Gamstedt, K., Schofield, E. "Keeping an eye on conserved ships, long-term monitoring: why and how?" in Proceedings of the *14th Meeting of the ICOM-CC - Wet Organic and Archaeological Material Group*, Portsmouth, May 2019. https://www.icom-cc-publications-online.org/4652/Keeping-an-Eye-on-Conserved-Ships-Why-Implement-Long-Term-Monitoring-

Book chapter

2017 Colson, A., Tamas, L. "The Bremen Cog, three recording techniques for one object". Book chapter in *Digital Techniques for Documenting and Preserving Cultural Heritage*, Arc Humanities Press.

2017 Ditta, M., Colson, A. "Total Station Surveying". Book chapter in *Digital Techniques for Documenting and Preserving Cultural Heritage*, Arc Humanities Press.

Conference publications

2015 Colson, A., Guery, J., Ditta, M. "*Bremen Cog* – Long term monitoring of deformation processes" Proceedings of the Conservation and Digitalization Conference, Condition 2015, Gdansk, Poland.

2018 Schmik, J., Colson, A., Hastedt, H., Luhmann, T. "Photogrammetrische Monitoring und Deformationsanalyse der Bremer Hanse-Kogge" in *Beiträge der Oldenburger 3D-Tage 2018.*

2018 Kuh Jacobi, D., Colson, A., Schilling, R. "Communicating conservation challenges in the exhibitions at the German Maritime Museum". In Proceedings of the *8th International Conservation Conference*, Szreniawa, October 2018.

2019 Colson, A. "Le monitoring des phénomènes de déformations des objets de grandes dimensions- Pourquoi et comment?" in Proceedings of the *Journées Nationales des Restaurateurs en archéologie*, Toulouse, Octobre 2016.

Invited talks and workshops

2014, September, COSCH Committee-Meeting, presentation "Case study Bremen Cog" Belgrade, Serbia

2015, May, Conference: Condition.2015 Conservation and digitization, presentation: "Bremen Cog – Long term monitoring of deformation processes using photogrammetry", Gdansk, Poland

2015, March, COSCH Committee-Meeting, presentation "Case study Bremen Cog", Saint Etienne, France

2015, September, COSCH Committee-Meeting, presentation "Case study Bremen Cog", Neuchatel, Switzerland

2016, March, COSCH Committee-Meeting, presentation "Case study Bremen Cog", Valetta, Malta

2016, September, COSCH Final Committee-Meeting, presentation "Case study Bremen Cog", Mainz, Germany

2016, October, Journée des restaurateurs en archéologie (JRA), presentation „Monitoring des phénomènes de déformation des objets du patrimoine de grande dimensions – Pourquoi et comment?", Toulouse, France

2016, December, Leibniz Jahrestagung, Bremische Botschaft, Representation of the German maritime Museum (DSM), Leibniz Institute of Maritime History, Berlin, Germany

2017, January, Rencontre du Groupe d'Étude et de Suivi des épaves restaurées (GEISER), presentation „État de la recherche sur le monitoring des phénomènes de déformation des objets de grandes dimensions ", Lyon, France

2017, June, 1st meeting of the European Working Group Monitoring of Preserved Ships (MoPS) and Faro Rhino Archaeological User Group (FRAUG) Meeting, presentation "Why shall we monitor deformation of ships in Museums?", Bremerhaven, Germany

2017, September, Saving Oseberg Project, Museum of Cultural History, University of Oslo, as DAAD guest scholar, "Deformation Monitoring of large-scale cultural heritage objects", Oslo, Norway.

2017, September, Conference from the International Society for Imaging Science and Technology, presentation: “Monitoring of Ships in Museums”, Lillehammer, Norway

2017, December, Participation to the yearly maintenance of the roman barge *Arles-Rhône 3*, Musée départemental Arles Antique (MDAA), presentation “Monitoring des phénomènes de déformation des objets de grandes dimensions”, Arles, France

2018, January, Conference Oldenburger 3D-Tage, presentation as second author: “Photogrammetrische Monitoring und Deformationsanalyse der Bremer Hanse-Kogge”, Oldenburg, Germany

2018, March, internal meeting from the chair for Digital Technologies in Heritage Conservation, Otto-Friedrich University, Bamberg, Germany

2018, March, Conference “3D – Durchblick oder Datenmüll? – Dreidimensionale Scan-Verfahren in der Konservierung/Restaurierung“, presentation: „Monitoring von Verformungsprozesse archäologischer Schiffe“, Dresden, Germany

2018, March, Scientific Colloquium from the German Maritime Museum (DSM), presentation „Deformation monitoring of large-scale cultural heritage objects- current state”, Bremerhaven, Germany

2018, May, yearly meeting from the working group Conservation/Restoration from the German Museum Association, “Die Überwachung der Bremer Kogge – Präventive Konservierung der 21. Jhd.”, Bremerhaven, Germany

2018, May, yearly meeting from the Science and Engineering in Arts, Heritage and Archaeology (SEAHA), Centre for Doctoral Training, University College London, presentation: “Preventive Conservation and 3D - A photogrammetry protocol for deformation monitoring”, London, Great Britain

2018, June, International workshop on Preventive Conservation from Leibniz Association, two presentations: 1) “Daylight Museums- Challenges for Preventive Conservation”; 2) “3D Technologies in Preventive Conservation – Monitoring of Deformation Processes”, Berlin, Germany

2018, September, Meeting from conservators of archaeological objects in Lower-Saxony, presentation: “3D Verfahren für langfristige Aufgaben – Hilfsmittel oder verschwendete Zeit”, Hannover, Germany

2019, January, scientific colloquium from the Institute for Archaeological Sciences, Heritage sciences and Art History (IADK), from Otto-Friedrich University, presentation of the PhD thesis, Bamberg, Germany

2019, May, Smithsonian Museum Conservation Institute, presentation “Spatial Monitoring for large-scale cultural heritage objects - The use of 3D for preventive conservation”, Washington D.C., United-States of America

2019, May, ICOM-CC Working Group conference Wet Organic Archaeological Material (WOAM), a session chair and two presentations: 1) “Keeping an eye on conserved ships – Spatial monitoring”; 2) “Bremen Cog spatial monitoring – the role of a conservator”, Portsmouth, Great Britain

Public outreach

2016, October, Rencontre École/Entreprises, Institut Français de Brême, presentation "Wie Sprachen und Denkmalpflege vorteilhaft sein können?", Bremerhaven, Germany,

2017, October, Club Science Institut Français, "3D technologies for ships- what for?", Oslo, Norway

2017, November, Science goes Pub'lic, "Neuen Technologien zur Überwachung von großen Museumsobjekten", Bremerhaven, Germany

2018, August, Kulturerbejahr "Konservierung der Bremer Kogge - Überwachung mit Hilfe digitaler Methoden", Bremerhaven, Germany

2021, March, 1st Archaeolgy Science Slam, Göttingen University, presentation: "Butter bei die Schiffe – damit die Kogge nicht zerfällt", (start 20:28, 10 minutes talk) https://www.youtube.com/watch?v=kK9cHvGfjOA&t=1349s

Teaching activities

2017, November, guest lecture on conservation ethics and deformation monitoring in the Master Program Digital Technologies in Heritage Conservation, Otto-Friedrich University, Bamberg, Germany

2018, November, guest lecture, Bachelor's program Conservation-Restoration of Cultural Heritage, École de Condé, Lyon, France

2019, January, guest lecture on conservation ethics and deformation monitoring in the Master Program Digital Technologies in Heritage Conservation, Otto-Friedrich University, Bamberg, Germany

2020, January, guest lecture on conservation ethics and deformation monitoring in the Master Program Digital Technologies in Heritage Conservation, Otto-Friedrich University, Bamberg, Germany

Scholarships

2016-2019 Doctoral Fellowship, German Maritime Museum (DSM), Leibniz Institute for Maritime History

2017, visiting scholarship from the German Academic Exchange Service (DAAD), two months, Museum of Cultural History, University of Oslo, Norway

Consulting activities and member of scientific committees

2017, November, Experts meeting on the future of the river barge Kaiserwerth, two presentations “Archäologische Schiffe in Museen” and “ EU-Arbeitsgruppe Überwachung von archäologische Schiffe in Museen“, Düsseldorf, Germany

2018, June, Museum Hamburger Bahnhof, Spatial Monitoring of the “Unschlitt/Tallow” from Josef Beuys (1977), Berlin, Germany

2019, May, Smithsonian American History Museum, participation to the scientific meeting on the Gunboat *Philadelphia* (1776), as coordinator of the MoPS Group, Washington D.C., United-States of America

Since 2020, member of the scientific advisory committee of the Museum of Cultural History, planning for the new Viking Museum, Oslo University, Norway

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9 LIST OF FIGURES

10 LIST OF TABLES

11 LIST OF ABBREVIATIONS

AD: Anno Domini used with a date to indicate the years after the birth of Jesus

DSM: Deutsches Schifffahrtsmuseum, translated into English as German Maritime Museum, Leibniz Institute of Maritime History, Bremerhaven (Germany)

CIPA: Comité International de la Photogrammétrie Architecturale, translated in English into International Committee of Architectural Photogrammetry, committee part of ICOMOS organization

COSCH: Colour and Space in Cultural Heritage

ECCO: European Confederation of Conservator-Restorers' Organization

GPS: Global Positions System

GNSS: Global Navigation Satellite System

IAPG: Institute of Applied Photogrammetry and Geoinformatics, Jade University of Applied Sciences Oldenburg (Germany)

ICOM: International Council of Museums

ICOM-CC: International Council of Museums – Committee for Conservation

ICOM-CC WOAM: International Council of Museums – Committee for Conservation working group Wet Organic Archaeological Material.

ICCROM: International Centre for the Study of the Preservation and Restoration of Cultural Property, based in Rome.

ICOMOS: International Council on Monuments and Sites

KHM: Kulturhistorik museum - Museum of Cultural History of the University of Oslo, Norway

SfM: Structure-from-Motion

SME: Small and Medium Enterprises

STSM Short Term Scientific Mission

TOF: Time-of-flight

UNESCO: United Nations Educational, Scientific and Cultural Organization

12 GLOSSARY

Accuracy:
Closeness of agreement between a measured quantity value and a true quantity value of a measurand (Joint Committe for Guides in Metrology (JCGM), 2012, p. 21)

Antishrink efficiency (ASE):
This calculation is used to evaluate the success of a treatment on modern wood and is looking at the differences of volume before treatment V_1 and after treatment V_2, expressed in percentage (Ross, 2010, p. 443).

$$ASE = \frac{V_2 - V_1}{V_1} \times 100$$

Archaeological wood:
"old wood that bears some traces of past cultural activity and that has been buried or otherwise removed from normal service for a period of time. This material has been divided into dry and waterlogged wood in recognition of the circumstances leadings to its preservation" (Schniewind, 1990)

Bundle adjustment:
Method for the simultaneous numerical fit of an unlimited number of spatially distributed images. It is also called bundle triangulation, it is the most powerful and accurate method of image orientation and point determination (Luhmann et al., 2020, pp. 349–350).

Calibration:
"Operation that, under specified conditions, in a first step, established a relation between the quantity values with the measurement uncertainties provided by the measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result form an indication" (Joint Committe for Guides in Metrology (JCGM), 2012, p. 28).

Condition report:
Assessment of an artefact or object's state of conservation at a given time. Used to document the object's 'health' over time.

Congruence analysis (CON):
A deductive approach using statistics based on congruence coefficient to analysis complex data sets. The index of similarity between points is quantified.

Conservation:
„All measures and actions aimed at safeguarding tangible cultural heritage while ensuring its accessibility to present and future generations. Conservation embraces preventive conservation, remedial conservation and restoration. All measures and actions should respect the significance and the physical properties of the cultural heritage item." (ICOM-CC Terminology)[174]

Creep (Fluage (fr) – Kriechen (de)):
Time dependent deformation under a certain applied load from a solid material. The material undergoes an increase in length, slowly and permanently.

Deformation:
Change in shape or size due to applied force or change in temperature.

Digitisation:
The process of converting from analogue to digital

Displacement:
Distance expressing a change of position within a reference frame, implying a movement.

Engineering Geodesy:
"Engineering geodesy is the production of geodetic information necessary for the planning of technical projects, setting out of the project design, control the correct construction, and monitoring of deformations" (Brunner, 2007)

Fault:
"Condition of an item that occurs when one of its component or assemblies degrades or exhibits abnormal behavior. Understood as a state not an event." (Czichos, 2013)

Failure:
"The termination of the ability of an item to perform a required function. Considered as an event and not a state." (Czichos, 2013)

Fisher-Snedecor distribution
also called F-distribution, is commonly used as probability theory to look into the two variances.

$$F = \frac{S_1}{S_2}$$

S stands for sample variance S_1 for sample 1 and S_2 for sample 2.

[174] http://www.icom-cc.org/242/about/terminology-for-conservation/#.YGMqoi222Cg

Finite-Element-Method (FEM):
Finite element methods (FEM) is a numerical procedure. The idea is to build links and interactions, called 'nodes', within the object of interest, some having known properties and others being unknow. A system of equations is established, and every 'nod' gets a material and structural properties. FEM helps to solve and compute complex physical problems. (Tezuka, 2006)

Geodesy:
"Geodesy is a science, the discipline that deals with the measurement and representation of the earth, including its gravity field, in a three-dimensional time varying space" (Vanicek and Krakiwsky, 1986, p 45)

Global Navigation Satellite System (GNSS):
Satellites placed in space provide geo-spatial positioning and the device on earth receives information on their location (longitude, latitude, and altitude).

Heritage science:
"Interdisciplinary research domain spanning the humanities and sciences. It focuses on enhancing the understanding, care, use and management of both tangible and intangible cultural heritage" ICCROM
"it should be seen as an umbrella term that encompasses conservation science, archaeological science and building science" (Strlič, 2018)

Laser tracker:
A mobile optical measuring device used in the industry to measure angles and distances using absolute interferometer distance measuring, which has the ability to track a target through 3D space.

Laser scanning:
Surveying instrument to measure distance and angles in a scanning. The emitted laser beam comes back from the surface and the distance is computed with the delay. (Hess, 2017)

Least-squares adjustment:
A method of determining the best value of an unknown quantity relating one or more sets of observations or measurements. (Collins English Dictionary, 2014)

Measurement:
"Process of experimentally obtaining one or more quantity values than can reasonably be attributed to a quantity" (Joint Committe for Guides in Metrology (JCGM), 2012, p. 16)

<u>Measurement error:</u>
"Measured quantity value minus a reference quantity value
NOTE 1 The concept of 'measurement error' can be used both
a) when there is a single reference quantity value to refer to, which occurs if a calibration is made by means of a measurement standard with a measured quantity value having a negligible measurement uncertainty or if a conventional quantity value is given, in which case the measurement error is known, and
b) if a measurand is supposed to be represented by a unique true quantity value or a set of true quantity values of negligible range, in which case the measurement error is not known.
NOTE 2 Measurement error should not be confused with production error or mistake"
(Joint Committe for Guides in Metrology (JCGM), 2012, p. 22).

<u>Measuring instrument:</u>
"Device used for making measurements, alone or in conjunction with one or more supplementary devices" (Joint Committe for Guides in Metrology (JCGM), 2012, p. 34).

<u>Measuring system:</u>
"Set of one or more measuring instruments and often other devices, including any reagent and supply, assembled and adapted to give information used to generate measured quantity values within specified intervals for quantities of specified kinds" (Joint Committe for Guides in Metrology (JCGM), 2012, p. 34).

<u>Metrology:</u>
Science of measurement and its application (Joint Committe for Guides in Metrology (JCGM), 2012, p. 16)

<u>Moisture content (MC):</u>
Moisture content is an indicator to estimate physical and mechanical properties of wood. It is calculated with the difference of weight before (m_{wet}) and after (m_{dry}) drying the wood in an oven, expressed in percentage (Ross, 2010, p. 80).

$$MC = \frac{m_{wet} - m_{dry}}{m_{dry}} \times 100\%$$

<u>Monte Carlo simulation:</u>
Computational method to analyze statistically results from complex systems. The input is randomized or altered in a structured way and its effect on the calculated output data observed (Luhmann et al., 2014, p. 547).

<u>Polyethylene Glycol (PEG):</u>
Is a polyether compound derived from petroleum used in medicine or cosmetic, and one of the most used bulking products in conservation of waterlogged organic material from archaeological context.

Photogrammetry:
"Photogrammetry encompasses methods of image measurement and interpretation in order to derive the shape and location of an object from one or more photographs of that object. In principle, photogrammetric methods can be applied in any situation where the object to me measured can be photographically recorder." (Luhmann et al., 2014, p. 2)

Preventive conservation:
"all measures and actions aimed at avoiding and minimizing future deterioration or loss. They are carried out within the context or on the surroundings of an item, but more often a group of items, whatever their age and condition. These measures and actions are indirect – they do not interfere with the materials and structures of the items. They do not modify their appearance"(ICOM-CC Terminology)[175].

Precision:
"Closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions" (Joint Committe for Guides in Metrology (JCGM), 2012, p. 22)

Remedial conservation:
"all actions directly applied to an item or a group of items aimed at arresting current damaging processes or reinforcing their structure. These actions are only carried out when the items are in such a fragile condition or deteriorating at such a rate, that they could be lost in a relatively short time. These actions sometimes modify the appearance of the items" (ICOM-CC Terminology).

Repeatability:
Set of conditions under which the measurement can be repeated with the same parameters (Joint Committe for Guides in Metrology (JCGM), 2012)

Resolution:
The distance that can be distinguished between two points.

Restoration:
"all actions directly applied to a single and stable item aimed at facilitating its appreciation, understanding and use. These actions are only carried out when the item has lost part of its significance or function through past alteration or deterioration. They are based on respect for the original material. Most often such actions modify the appearance of the item" (ICOM-CC Terminology)[176].

[175] http://www.icom-cc.org/242/about/terminology-for-conservation/#.YGMqoi222Cg
[176] http://www.icom-cc.org/242/about/terminology-for-conservation/#.YGMqoi222Cg

Rigid body:
Solid body in which deformation is considered a zero or can be neglected.

RMS (Root-Mean-Square):
The root-mean-square or root-mean-square-error (RMSE) indication of error often used to express the standard deviation

Signal-to-noise ratio (SNR):
Measure used to compare the level of signal to the background noise.

Standard deviation:
The variation between the true value and the measured value, which always combines the true value and errors (random and standard).

Student's t-distribution:
Also called simply the t-distribution is symmetric and bell-shaped like the normal distribution, but with heavier tails, producing more values far from its mean.

Strain (tension (fr) – Spannung (de)):
A geometrical measure of deformation representing the relative displacement between particles in a material body.

Structure:
Assemblage of interconnected components forming a system, which remain in equilibrium. For instance, a building is a combination of beams and columns that constitute together a certain structure. Bridges, retaining walls, dams are other kind of structures.

Structure-from-Motion (SfM):
Image-based measuring system based on photographs developed in computer vision using algorithms detected automatically similar features in several images at a time.

Surveying:
Classical surveying products (plans, sections, facades) are two dimensional plans. Since 2000 increasingly: The process of recording and examine a structure three dimensionally.

Symptom:
"Perception made of means of human observation and measurements, which may indicate the presence of an abnormal condition with a certain probability" (Daum, 2013).

Syndrome:
"Group of symptoms that collectively indicate or characterize an abnormal condition" (Daum, 2013).

Systematic error:
"Component of measurement error that in replicate measurements remains constant or varies in a predictable manner" (Joint Committe for Guides in Metrology (JCGM), 2012, p. 22).

Targeting:
The process of installing targets on a structure. Similar to signalling.

Terrestrial laser scanning (TLS):
"measure distances with known angles to a surface of an object at high speed, using a laser beam, in order to produce 3D coordinates." (Hess, 2017)

Three-dimensional measuring system:
See measuring system. The three-dimensional measuring system deals with 3D measurement.

Traceability:
Property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty. (Joint Committe for Guides in Metrology (JCGM), 2012, p. 29)

Total station (TS):
"A total station is a direct surveying instrument using laser light. The distance between the instrument and the target is measured and recorded digitally". (Ditta and Colson, 2017)

True value or true quantity value:
True value is the ideal value of quantity, which is the property of a phenomenon, body or substance expressed as a number (Joint Committe for Guides in Metrology (JCGM), 2012).

Uncertainty:
"Uncertainty of a measurement: non-negative parameter characterizing the dispersion of the quantity values being attributed to the object measured, based on the information used. It includes components arising from systematic effects, such as components associated with corrections and the assigned quantity values of measurement standards." (Joint Committe for Guides in Metrology (JCGM), 2012, p. 25).

Appendix A. Non-Exhaustive List of Shipwrecks in Museums

Liste non exhaustive des épaves en musées
(Au 1er juin 2016 établie par Marine Crouzet et Laure Meunier, complétée par A. Colson 2021)

Allemagne
Bonn
Xanten
Bonn
Zwammerdam 3
Bremerhaven
*Cog**
Bremerhaven
*Karl**
Bremerhaven
Oberlander
Constance
Pirogue
Constance
Barge
Düsseldorf
Kaiserwerth
Mayence
*Bateau romain 1**
Mayence
*Bateau romain 2**
Mayence
*Bateau romain 3**
Mayence
*Bateau romain 4**

Mayence
*Bateau romain 5**
Mayence
*Bateau romain 6**
Mayence
*Oberstimm 1**
Mayence
*Oberstimm 2**
Haithabu
Haithabu 1
Husum
Uelvesbuel
Schleswig
Nydam

Angleterre Portsmouth
*Mary-Rose**
Dorset
Poole logboat
Douvres
Dover boat

Australie
Fremantle
*Batavia**

Belgique
Ath
Pommeroeul 1
Ath
Pommeroeul 2
Anvers
Doel (en cours)

Canada
Québec
*Epave civi.**
Red Bay
C halupa

Chine Quanzhou
*Quanzhou**

Chypre
Kyrenia
Kyrenia

Corée du Sud
Mokpo
*Shinan**
Mokpo
*Dallido**
Mokpo
*Wando**

Croatie
Nin
*Conduracroatica 1**
Nin
*Conduracroatica 2**

Danemark
Copenhague
Hjortspring
Roskilde
*Skuldelev 1**
Roskilde
*Skuldelev 2**
Roskilde
*Skuldelev 3**
Roskilde
*Skuldelev 5**
Roskilde
*Skuldelev 6**

Roskilde
*Roskilde 6**

Espagne
Bilbao
Urbieta
Bilbao
Mazarron 1

Estonie Lennusadama
Maasilinn
Talinn
Cog

Etats-Unis
Austin *La Belle**
Washington DC *Philadephia*

France
Arles
*Arles Rhône 3**
Lyon
*LSG1-couzonnaire**
Grenoble
*LSG15**
Marseille *Bourse/Lacydon**
Marseille
Samaritaine
Marseille
*JV3**
Marseille
*JV4**
Marseille
*JV7**
Marseille
*JV8**
Marseille
*JV9**
Noyen
Barque
Cognac
Pirogue
Lons-le-Saunier
Pirogue
Lons-le-saunier
Pirogue de Chimay
Brégnier
Pirogue
Rennes
Pirogue
Gueugnon
Pirogue
L'union
Pirogue 1
L'union
Pirogue 2
Eyzies-Bercy
Pirogue
Paris-Bercy
Pirogue 2
Paris-Bercy
Pirogue 3
Paris-Bercy
Pirogue 6
Paris-Bercy
Pirogue 8
Sanguinet
Pirogue 5
Tardinghen
Barque

Israël
Haïfa
Ma'agan Mikhael
Ginosar
Jesus'boat

Italie Fiumicino
Fiumicino 1
Fiumicino
Fiumicino 2
Fiumicino
Fiumicino 3
Fiumicino
Fiumicino 4
Fiumicino
Fiumicino 5
Marsala
Marsala1
Marsala
Marsala 2
Aquileia
Monfalcone
Comachio
Comachio
Sardaigne
Olbia

Norvège
Oslo
*Oseberg**

Oslo
*Tune**
Oslo
*Klastad**
Oslo

Gokstad

Pays-Bas Amsterdam
*De Meern 1**
Utrecht
Utrecht 1
Woerden
Woerden 7

Pays-de-Galle
Newport
Medieval ship (en cours)

Pologne
Gdansk
Gdansk 1

Suède
Goteborg
Askekarr 1
Stockholm
*Vasa**
Suisse Neuchâtel
Pirogues Bevaix
Yverdon
*Yverdon 1**
Yverdon
*Yverdon 2**

Turquie
Bodrum
Uluburun
Istanbul
Yenikapi (en cours)

Zone	**Nombre d'épaves**
Allemagne	19
France	26
Europe	88
Monde	101

Appendix B.
COSCH – Report STSM – Structure-from-Motion

Image-based 3D modelling of the Bremen "Cog"

Reference: Short Term Scientific Mission, COST TD1201
Beneficiary: Julien Guery, Geoarchaeologist and specialist of Photogrammetry, Scientific Project leader at Captair Company, 5 rue de la Grande Fin, 21121 Fontaine-lès-Dijon, France. julien@captair.net
Host: Amandine Colson, Conservator of archaeological objects, Deutsches Schiffahrtsmuseum, Hans-Scharoun-Platz 1; 27568 Bremerhaven, Germany. colson@dsm.museummailto:colson@dsm.museum
Period: on-site work from 21.10.14 to 25.10.14, data processing from 27.10.14 to 28.11.2014
Reference code: COST-STSM-TD1201-061014-048805

1. Purpose of the STSM

a. Introduction – Case Study

The *Bremen Cog* was discovered in 1962 in the River Weser close to the city of Bremen. It was successfully conserved and restored during the following years at the German Maritime Museum and since 2000 the ship is on display. This medieval vessel is 24 m long, 7 m wide, 4 m high and belongs to the largest archaeological ships exhibited in Europe with the *Vasa* in Stockholm (Sweden) and the Mary Rose in Portsmouth (England).

Although the conservation treatments are completed, it is absolutely necessary to lead further monitoring measures in order to control regularly the state of the ship. The monitoring must include the environment control in the room, standards in Preventive Conservation (Temperature, Relative Humidity and Light), but also deformation processes. The environmental measurements are already on-going, but the deformation of the wood on the other hand is not monitored yet.

A three-dimensional monitoring of the Ship would allow the museum's conservator to keep an eye on the ship and wood deformation that occurred in the past and possible ones to come in the future. Until now the *Vasa* and the *Mary-Rose* are monitored with a *Total station*, electronic version of the traditional Theodolite, using different settings to get a 3D model, twice a year in average, comparing the data from the last measurements in order to monitor and try to understand deformation processes.

In 2013, Dr. Ursula Warnke (Museum's Director) and Amandine Colson (Museum's Conservator) joined the COSCH action. After the Meeting in Joensuu, Finland, it was decided to select some objects for a case study, which could help the experts to document better the way every technology is used but also to provide guidelines for other museum professionals. The German Maritime Museum, responded to that call proposing the *Bremen Cog*.

In fact, in the field of conservation-restoration of large-scale objects, ships represent one major issue. In fact, coming from archaeological, historical or even industrial context, the size of the object, its buoyancy (when still floated) and its technical features are rising great challenges when they are to be displayed in a museum.

The *Bremen Cog* was conserved with Polyethylene Glycol (PEG), a method broadly used for waterlogged archaeological organic material, moreover for wood, and researched internationally among others from the Wet Organic Archaeological Material Group (WOAM) from the International Council of Museums Committee for Conservation (ICOM-CC).

The Museum is also facing a great development phase, since 2009 due to a new direction.
In 2015, the Museum celebrates its 40th Anniversary and an exhibition will be set up around the ship opening to the public in September. Beginning 2016 an extensive renovation campaign of the two Museum's Building: "Scharoun", the historical one, and "Bangert", opened in 2000, will start.
Therefore, the opportunity of having a 3D model of the Ships is not only a support for the conservation-restoration but would also be the chance to continue to present it during the building works at the museum. The data may also be accessible on the Internet, thus giving the possibility for researchers to gain access to it.
After the renovation a 3D reconstruction of the cog in the exhibition could become one of the main attractions for the public, especially for the young public.

This STSM is the first of a series of missions in the framework of the case study: « 3D model of the *Bremen Cog* » (2014-2016) accepted last September in Belgrade[177].
The main goal is on one hand to compare the data, the acquisition methods, the costs and the data processing from different technologies and on the other hand to combine and fuse the 3D Data produced. In fact, is it clear that every technology has its strengths, which lay usually on different technical issues.
List of other STSM or actions planned for the Case Study:
Photogrammetry: STSM Captair, October 2014
3D Laser Scan: I3 Mainz, November 2014
Total Station: DSM, summer 2015
Data Fusion: STSM University of Szeged, autumn 2015

Every technology is to be at first thought as a single one that could reach the general goal: **settling a monitoring technique to document the deformation processes on-going on the ship and visualize the ship for the Museum's visitors during the renovation campaign. This monitoring must be reproducible, with a given protocol, gear list and general costs.**

[177] See Case Study application on www.cosch.info

b. Our Mission

During this mission the purpose was the production of a 3D model through Structure from Motion Photogrammetry (SfM) in order to determine if a systematic acquisition protocol could be developed, which could at some point be reproduced by the museum's staff.
Photogrammetry is based on making measurements from photographs[178]. A series of pictures are done all around an object and processed together with a specific software, which will detect common points. These points are the ones that are present at least on two pictures, that the software uses to build up a three-dimensional model. Unlike other technologies that require unavoidably targets to build up a point of reference, Photogrammetry operates for itself. Only a digital camera is today necessary to start an acquisition. Even smartphones could theoretically be a support to produce a photogrammetric model, but of course depending on the quality of the images, the 3D model can be very precise, down to the µm in some case and the more covering up between pictures you have, the better it is.
The aim of the protocol is at first to enable a 3D monitoring process of the *Bremen Cog*, and one day to conduct further acquisition operated by the museum's staff. After all as soon as the operator has some basic knowledge about the technical issues, photogrammetry is relatively accessible. The complicated task lays in the conceptualization of the protocol.
Our main objectives were:

- the production of an image-based 3D model
- the extraction of Digital Elevation Models (DEM)
- the identification of technical issues linked to Photogrammetry
- the determination of recommendations for future acquisitions

Contribution to actions objectives

This Short Term Scientific Mission contributes to the objectives of implementation of new technologies for the documentation of a cultural artefact.
Therefore this is a good support for the Working Group 4: Documenting the conservation process and using imaging method. The WG4 current task "Identification, structuring and implementation of typical use cases" Sub task 2: "Review of current and future needs of the conservation field towards optical measurements"[179]. The work achieved during this mission has a direct link with these goals.
As described earlier, this STSM is linked with a Case Study and other Missions, some to come in 2015-2016, all creating a basis for data fusion and comparison of different measuring method (2nd STSM, Z. Kato, 2015 ; WG2 : spatial objects documentation).

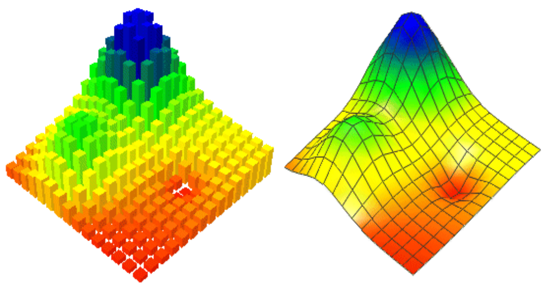
[178] Wikipedia Consulted January 2015: http://en.wikipedia.org/wiki/Photogrammetry
[179] See WG4-Sub-task 2- Piccolo, Novembre 2014

The Case Study of the *Bremen Cog* is combining the documentation purpose for the conservators and archaeologists take care of the objects but also includes dissemination and visualization to the public. This topic is linked to the work done within the Working Group 5 : Visualisation for the Cultural Heritage object and its dissemination, moreover the task 1: Identification, planning, implementation and testing of typical applications of visualisation.
Since 2012 the Leibniz Association in Germany, whom the Deutsches Schiffahrtsmuseum is a member, advocates the importance of sharing scientific results with the Public in an action called *Schaufenster der Forschung* (Window to Research). Our initiative results from the wish to enhance the contact with our visitors and to let them experience more of the scientific and researchers world within the exhibition.
Thanks to the synergy from the Early Stage Researchers-Think Tank during Task Force Meeting of Joensuu (Finland) in April 2014, two European cultural heritage actors (CAPTAIR Company and the Deutsches Schiffahrtsmuseum) could meet and work together.
This European cooperation for Colour and Space documentation of a cultural heritage artefact also finally contributed to the global COSCH objective.

Description of the work carried out

Theoretical approach

Photogrammetry is nowadays widely used in Archaeology and Geology/Geomorphology to document states of work and to support the work on-going, but also to monitor geological phenomena on a long-term rate. In fact, Geologist or Geomorphologists are willing to monitor "slow" phenomena carried out within decades or centuries, actually the same issues that the conservators are facing with the Cultural Heritage Object. However, it is not exactly the 3D model that is used, but the data coming from it and produced with the pictures, a so-called *Digital Elevation Model*, DEM. In other words, we speak about a topographical image like on a map in relief showing mountains given by the altitude data. It is from this notion that the methodology of this work results from.
The results aim to be precise down to centimetres, which is for now precise enough to detect deformations processes.



Digital Elevation Model (DEM) [180]

[180] 1999 - Kidner, Dorey, Smith; "What's the point? Interpolation and extrapolation with a regular grid DEM", Proceedings from the 4th International Conference on GeoComputation, Fredericksburg, Virginia, United States of America

a. Gear

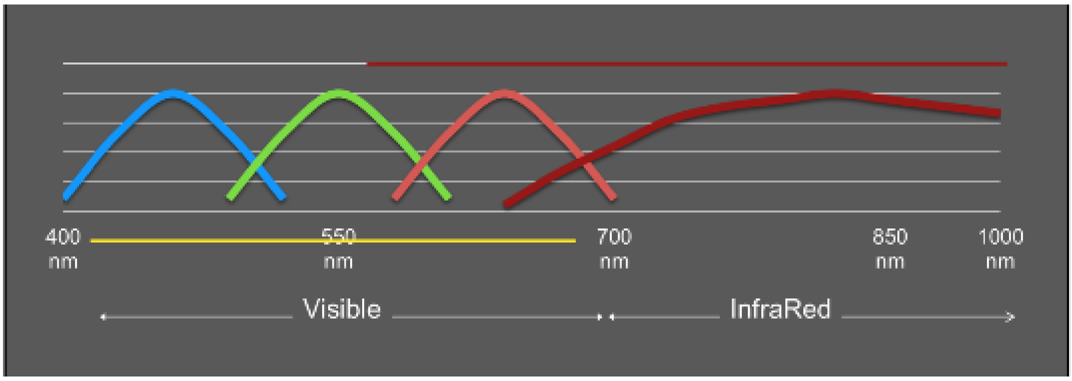
After the evaluation of the field constraints, four cameras with different camera lenses were tested:

- Canon EOS 5D MarkIII, full frame with 50mm camera lens (provided by Captair)
- Nikon D300, APSC with 18mm equivalent 27mm camera lens (owned by the museum)
- Canon IXUS RGB, compact camera with 24mm camera lens (provided by Captair)
- Canon IXUS NIR (Near InfraRed), compact camera with 24mm camera lens (provided by Captair)

All treatments were operated with **Agisoft Photoscan Pro 1.0.3.**

Why Near InfraRed

Using a camera that near InfraRed range allows us to a dynamic range more over under dark lightening conditions. The dark wood of the *Bremen Cog* makes difficult to get outline of each plank or frame.



Near Infra Red photos : get the largest dynamic range - Guery © 2015

b. Setting up - Day 1

The acquisition began on the morning of 22.10.2014. The first step was to study the environment of the ship in order to define the possible positions for photo acquisitions. Indeed, only an on-site evaluation of the field constraints and a few tests make it possible to determine a sustainable acquisition strategy.

One of the main difficulty is the surrounding, the concrete structures of the building are really close to the ship (less than 5m). All the photos have to be taken close to the ship because of this concrete structures. Thus all photos have a restrain field of view. One of the requirements of SfM photogrammetry being a good photo covering of the studied object, it implies a larger number of photos than in a clear environment with no obstacles.

The concrete structures are an obstacle for acquisition on the ground floor, but on the other hand gives access to a first and second floor, enabling to complete the dataset with photos taken from a point of view inaccessible from the ground floor.

The second main difficulty is that, as the ship is exhibited in an open hall, with large windows providing intense natural lightning and numerous spotlights, the camera parameters have to be constantly adapted as the lightning conditions are changing.

Last but not least, since 2006, the Ship is supported some kind of scaffolds, metallic structure installed to enable the reshaping of the whole ship, moreover the support of the hull, and never taken away, since no one knows if the wood is stable.

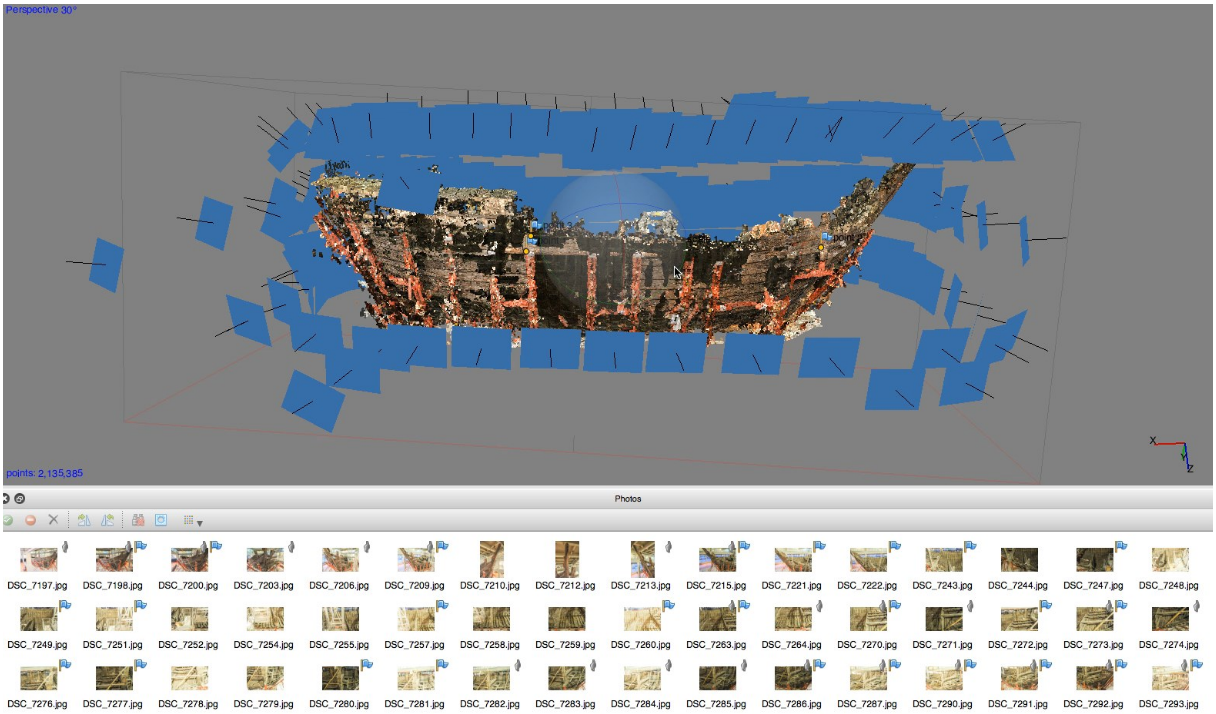
On that day, tests were concentrated on the ground floor.

Each acquisition has been pre-treated on-site to determine which camera/camera lens was appropriate to this STSM issue, but also to determine the appropriate number of pictures to allow a high level of precision.

The important phase is of course to control the alignment of pictures and their positioning.

Six targets provided by I3Mainz were also placed to the concrete structure and to the metallic structure supporting the ship in order to proceed to the scaling of the 3D model, and to have fixed points for future acquisitions and data fusion. The coordinates of the targets points were measured and documented.

In the evening the first processing was launched in order to check if the positioning was correct and to refine or adjust it.



Dense surface model Photogrammetry in Agisoft “Photoscan”

c. First Results - Day 2

Canon EOS 5D photos gave the best results in terms of accuracy and density of the final dense point cloud. But the use of 50mm camera lens was not appropriate on most parts of the ship because of the concrete structure and the reduced field of view induced.
Nikon D300 photos produced acceptable results, even though the dense point cloud contained a lot of “noise”, meaning geometric artefacts induced by photo aberrations. Furthermore the camera lens was not stabilized and was fully manual, and technical photographic knowledge is needed to use it properly. With no photographer in the museum staff, its use in a repeatable acquisition protocol seems compromised.
Canon IXUS RGB and NIR photos gave good results, accurate enough for the production of DEMs, with less noise with NIR photos. Canon IXUS combine a large field of view (24mm), enabling to lower the number of photos with a short shooting distance, and fully automated settings needing no technical photographic knowledge.
A new set of NIR photos was acquired on the morning of 23.10.2014 on the ground floor, the first and the second floor. The acquisition in the early morning gave the possibility to have minimal lightning troubles as spotlights were off until 9 a.m. and the natural lightning was low.
After this acquisition the first results were presented to the museum’s directory and future research collaborations were discussed for new exhibitions and dissemination issues.

The afternoon was dedicated to data processing in order to define methodological recommendation adapted to the field constraints. From the observation of the different results, adjustments were made to the acquisition protocol: reducing the number of photos and identify precise photo positions.

d. Final acquisition - Day 3

The protocol was tested and repeated on the 24.10.2014 both with Canon IXUS NIR and Nikon D300 (camera owned by the museum). The acquisition were experimented with different times of the day to determine the best lightning conditions. As first conclusions, it appeared that the best time for acquisition was on the early morning, or in the evening, with minimal sunlight and spotlights on.
On the afternoon, the methodological recommendation were transmitted to the conservator and she operated a first acquisition on her own. This acquisition was operated with the Nikon D300 camera owned by the museum. The analysis of the dataset produced revealed that, if the methodological recommendation were clear enough to implement a reproducible acquisition protocol, some technical photographic training was needed.

e. Data Processing

Like during the acquisition in Bremerhaven, the treatments were operated with **Agisoft Photoscan Pro 1.0.3.** During the next weeks, several post treatments were operated:

- post-processing of the photos from the different sets: light optimization, cameras calibrations
- virtual removing of the metallic structure supporting the boat
- Extraction of DEMs on different sides of the boat
- Extraction of an animation of the 3D point cloud for scientific dissemination (used by the conservator during a conference).

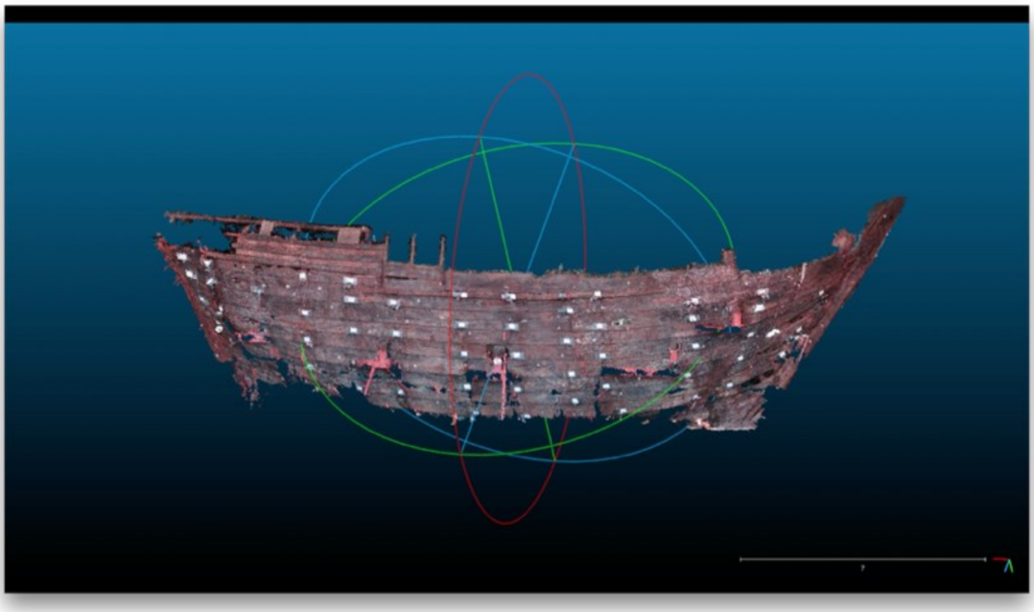
2. Description of the main results obtained

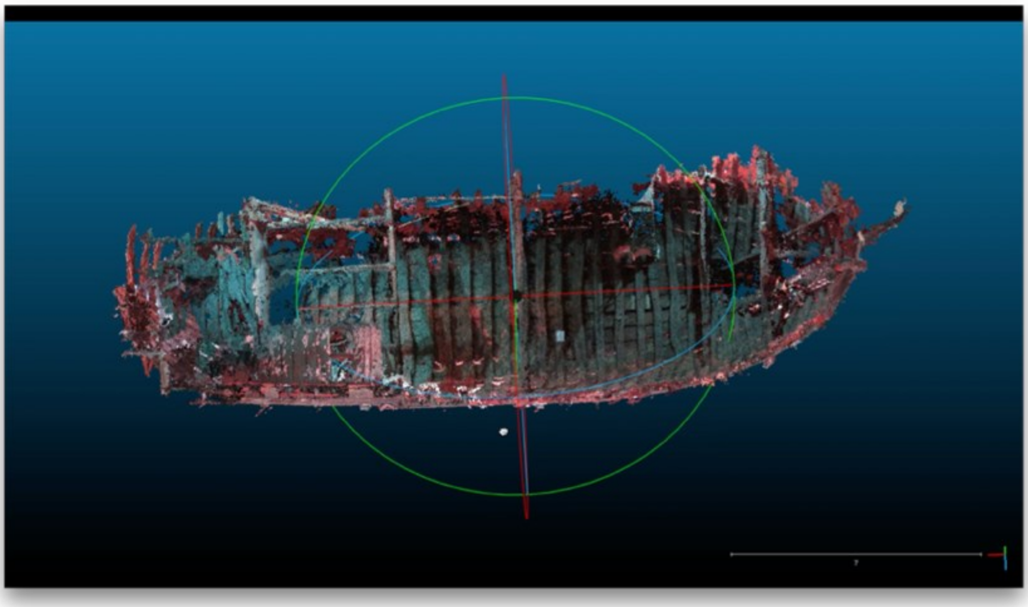
All in all, around 200 pictures has been necessary to provide an appropriate 3D model. The use of a camera tripod because of the lightning issues but also use the manual mode was not easy to handle for an unexperienced user. The camera of the museum needs to be adjusted in order to provide better images. The suggestion to buy a new lens was made.
This STSM resulted into an image-based 3D documentation:

- photos of the outside of the ship
- photos of the inside of the ship
- 3D dense point cloud of the entire ship (outside and inside)
- DEM of each side of the ship
- and 3D animation of the ship for dissemination

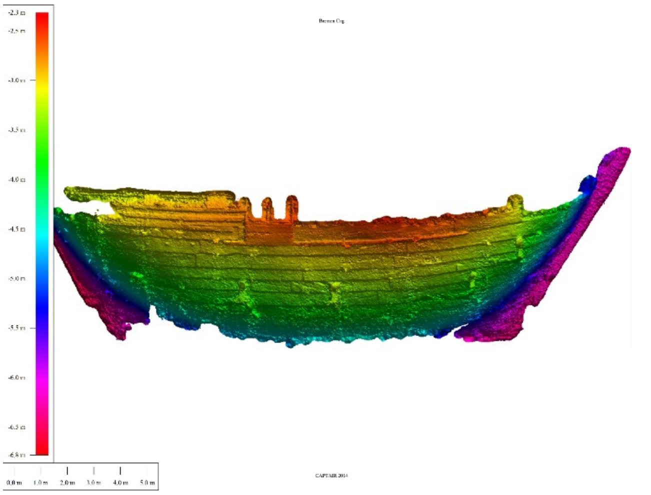
A guidelines map was also produced to explain the photo strategy for a good acquisition. It was based on the architectural plans of the building, using the concrete structures as frames for the different positions of photos.

3D dense point cloud of the ship - Number of points: 7, 7 millions



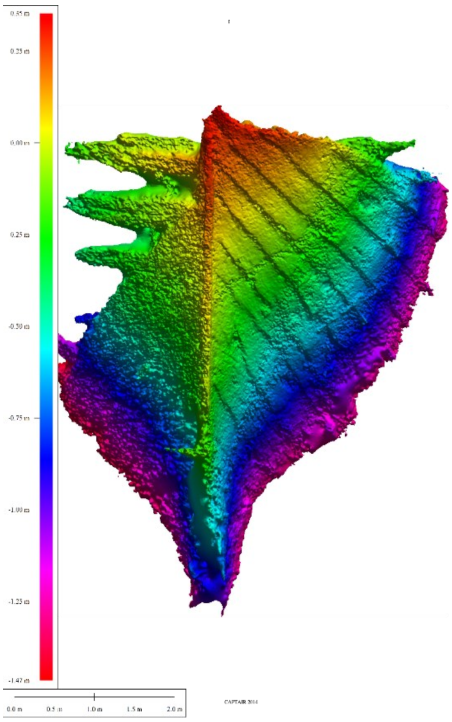


DEMs of the ship- Ground Resolution: 5mm



Face A

Zenithal view

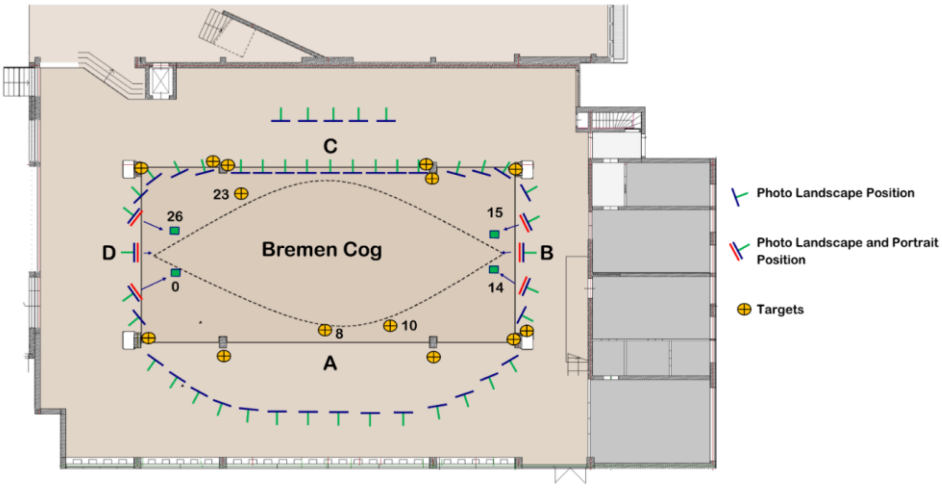


Face D

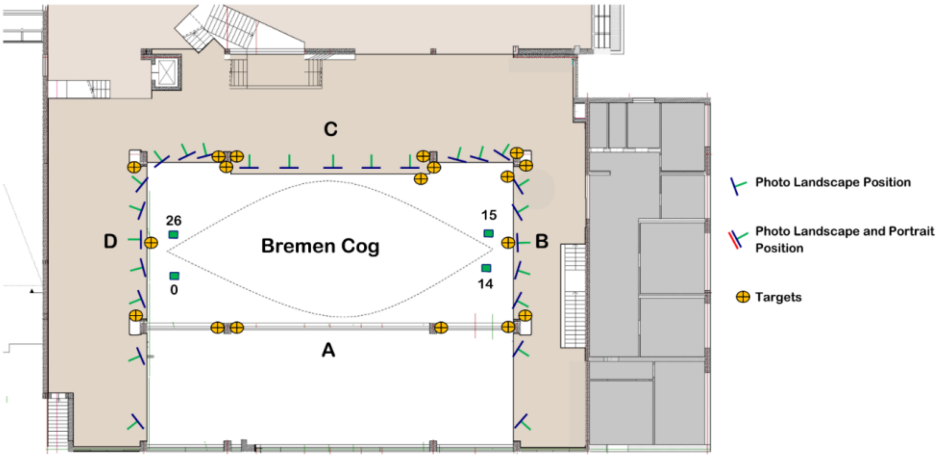
Guidelines map – Cog's Exhibition Hall

Note: on these maps the target points from the STSM are mentioned as well as the one installed during the mission from I3Mainz in November 2014

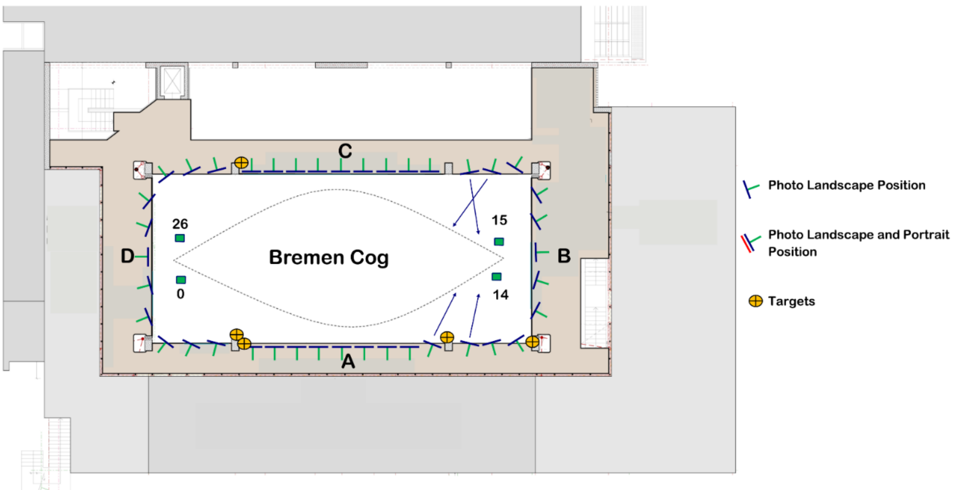
Ground Floor



First Floor



Second Floor



3. Future research including collaboration with the host institute

This mission showed us that the end-users must be trained on a basic level to be able to understand the process but also to be able to conduct an acquisition themselves even if the data processing is done by someone else. Further work together with the conservator to adjust the results is necessary. Perhaps through another STSM.

Like described earlier, the museum plans to celebrate in September its 40th anniversary and to open a new exhibition unit around the ship. The integration of 3D modelization in the exhibition process is planned.

4. Projected publications/articles resulting or to result from the STSM

Julien Guery is invited in March 2015 at the triennial meeting from the German Restorers Association working group: Archaeological Object, to give a presentation about his work. Another article would be prepared for 2015 when the second acquisition is carried out at the museum to report about the monitoring system and assess if the photogrammetric is sustainable.

Amandine Colson, will report about this work in March during the next COSCH Meeting and further comments would come from the COSCH community.

5. Confirmation by the host of the successful of the mission (with Signatures)

We confirm that Julien Guery from Captair, worked at the Deutsches Schiffahrtsmuseum from the 21.10.14 to the 25.10.14.

The mission was very successful and the results very promising. This collaboration and moreover the fact that the museum was fully involved in the process was very inspiring for future projects.

Documentation of large scale historical or archaeological artefacts is not an easy task and monitoring them for long term research is also very challenging. Therefore we are very thankful to Captair and the COSCH network for the excellent work that has been accomplished.

We are looking forward to present the results to our colleague during the next COSCH Meeting.

Amandine COLSON, M.A. Conservator at the Deutsches Schiffahrtsmuseum

Dr. Ursula Warnke, Director at the Deutsches Schiffahrtsmuseum

6. Financial Summary

Grant amount: 750 €

« On site » work from 21.10.14 to 25.10.14:

Location: Bremerhaven (Germany), Deutsches Schiffahrtsmuseum

1) Travelling Expenses:

- Train tickets Dijon - Paris Charles de Gaulle : 68.00 €
- Plane tickets Paris Charles de Gaulle - Hamburg : 287.84 € + 15.00 € (Luggage)
- Bus tickets Hamburg - Bremerhaven : 12.99 €

Time travelling: 2 days

Total: 383.83 €

2) Accommodation and daily expenses :

15 meals (3 per day):

- breakfast 5€ : 25€
- lunch 15€ : 75€
- diner 20€ : 100 €

Total: 200 €

Museum's Guest room: 20 € per day: 80€

Expenses offered by the museum

Data processing from 27.10.14 to 28.11.2014:

Location: Dijon (France), Captair Company

Budget available: 166, 17 €

7. Potential interdisciplinary value of research carried out and any other comments

Thanks to the COSCH action, we have been able to work on a conservation-restoration problematic involving Photogrammetry. Until now no guidelines has been published for the documentation of large scale objects in the specialized literature. This technique allow a lot of freedom in the settings, but also in terms of gear necessary to proceed to an acquisition. A good professional and reflex camera can be used, which usually all museums already own. If it is not the case, the investment is worth, because it can be used for other purposes.

Therefore, it is a very attractive technique for Cultural Heritage Institutes willing to monitor objects systematically or on a long-term scale.

This experimentation has interdisciplinary value in 3 different ways:

- combination of teledetection methodology and conservation issues
- crossing of multispectral imagery and 3D imagery
- communication and valorisation of an archaeological artefact through ongoing research work
- Public understanding of research (monitoring and documentation)

Appendix C.
COSCH – Report STSM – Total Station

Total station recording and monitoring of the Bremen "Cog"

Short Term Scientific Mission - COST TD1201

Massimiliano Ditta
Maritime Archaeology Programme
University of Southern Denmark

Total station recording and monitoring of the Bremen "Cog"

REFERENCE: Short Term Scientific Mission, COST TD1201
Beneficiary: Massimiliano Ditta, maritime archaeologist with expertise in digital recording and surveying of ships and boats - University of Southern Denmark; Esbjerg, Denmark.
massimiliano.ditta@outlook.com
Host: Amandine Colson, Conservator of archaeological objects, Deutsches Schiffahrtsmuseum, Hans-Scharoun-Platz 1; 27568 Bremerhaven, Germany.
colson@dsm.museummailto:colson@dsm.museum
Period: from 07/04/2015 to 28/04/2015
Place: Deutsches Schiffahrtsmuseum, Hans-Scharoun-Platz 1; 27568 Bremerhaven, Germany
Reference code: COST-STSM-TD1201-25185

1. Purpose of the STSM

1.1. Introduction – Case Study

The *Bremen Cog* was discovered in 1962 in the River Weser close to the city of Bremen. It was successfully conserved and restored during the following years and since 2000 the ship is on display. This medieval vessel is 24 m long, 7 m wide, 4 m high and belongs to the largest archaeological ships exhibited in Europe with the *Vasa* in Stockholm (Sweden) and the *Mary Rose* in Portsmouth (England).

Although the conservation treatments are completed, it is absolutely necessary to lead further monitoring measures in order to control regularly the state of the ship. The monitoring must include the environment control in the room, standards in Preventive Conservation (Temperature, Relative Humidity and Light), but also deformation processes. The environmental measurements are already on-going, but the deformation of the wood on the other hand is not monitored yet.

In 2013, Dr. Ursula Warnke (Museum's Director) and Amandine Colson (Museum's Conservator) joined the COSCH action. After the Meeting in Joensuu, Finland, in March 2014 it was decided to select some objects for case study, which could help the experts to document better the way every technology is used but also to provide guidelines for other museum professionals. The German Maritime Museum, responded to that call proposing the *Bremen Cog*.

In the conservation-restoration field large scale objects like ships represent one major issue. In fact, coming from archaeological, historical or even industrial context, the size of the object, its buoyancy (when still floated) and its technical features are rising great challenges when they are to be displayed in a museum.

The *Bremen Cog* was conserved with Polyethylene Glycol (PEG), a method broadly used for waterlogged archaeological organic material, moreover for wood, and researched world-wide among others from the Wet Organic Archaeological Material Group (WOAM) from the International Council of Museums - Committee for Conservation (ICOM-CC).

This STSM is the third of a series of missions in the framework of the case study: « 3D model of the *Bremen Cog* » (2014-2016) accepted last September in Belgrade[181].
The main goal is on one hand to compare the data, the acquisition methods, the costs and the data processing from different technologies and on the other hand to combine and fuse the 3D Data produced. As a matter of fact every technology has its strengths which lay usually on different technical issues, but for every case, we should use them intentionally and not only by chance.
List of other STSM or actions planned for the Case Study:

- Photogrammetry: STSM Captair, October 2014
- 3D Laser Scan: I3 Mainz, November 2014
- Total station: STSM University of Southern Denmark, April 2015
- Data Fusion: STSM University of Szeged, autumn 2015

Every technology is to be at first thought as a single one that could reach the main goal: settling a monitoring technique to document the deformation processes on-going on the ship and visualize the Ship for the Museum's visitors during the renovation campaign. This monitoring must be: reproducible, with a given protocol, gear list and general costs.

1.2. Total station recording and monitoring of the Bremen "Cog": Goals

Recording of control points with a Total station is a very flexible and accurate method to produce simple 3-dimensional point data of a structure. The result are extremely accurate and can be used for very different purposes:

- High definition dataset for monitoring: the method consents the acquisition of points in 3 dimensions, both for the outline of the shapes and sensible structures of the current boat. Given the high accuracy (± 2 mm), the acquired dataset can be compared with subsequent datasets to measure differences and changes in the position of the datum points. The comparison can lead to the understanding of deformations and help to take further decision concerning restoration issues in the future.

- Define a reproducible protocol for the conservation monitoring: once the protocol is defined, it will possible for the museum to repeat the acquisition of the datum points and to compare the results with previous datasets. This will provide a durable monitoring system of the *Bremen Cog*.

2. Contribution to actions objectives

Spatial objects documentation (WG 2): Total station recording.

1st WG task st2.1: Identification of the main 3D scanning techniques suitable for use in CH objects.

st2.2: Analysis and comparison of the different 3D scanning techniques. The actual performance of the techniques identified for different types of CH objects will be analysed in great depth based on the identified setups and available expertise. The goal is to analyse the advantages and limitations of these techniques depending on the deciding characteristics, and to stimulate new developments to address the identified drawbacks.

Analysis and restoration of Cultural Heritage surfaces and objects (WG 4): surface monitoring of the Ship, not provided by the coordinate measuring technique used by the museum for monitoring the Ship.

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[181] See Case Study application on www.cosch.info

1st WG task st4.1: Identification, structuring and implementation of typical use cases surface analyses based on various optical, physical or chemical characteristics may serve diverse purposes. Surface characteristics are subject to the interaction with the optical radiation and the process of data capture. It is therefore important for COSH to identify crucial factors affecting these processes and to establish a reliable knowledge base.

2nd WG task s4.2: Development of guidelines. Similarly, it is important to identify and define the impact of the instrumentation on the quality of results. Critical steps in the analytical process should be identified depending on the purpose of the undertaken analysis.

3. Description of the work carried out

3.1. Total station as monitoring device

The total station is a composite technology which allows a selective recording without direct contact between instrument and object. The device integrates the functions of a theodolite (transit) (figure 1) for measuring angles, with an electronic distance meter (EDM) and a digital recorder.

Angles and distances are measured from the total station to points under survey, and the coordinates (X, Y, and Z or easting, northing and elevation) of surveyed points relative to the total station position are calculated using trigonometry and triangulation. The final output is a sequence of points with 3-dimensional coordinates in relation to a local or geographical reference system. Total stations has traditionally been employed for surveying or as a tool to record context and establish references for other technologies, as well as for monitoring of sensible structures as dams and bridges.

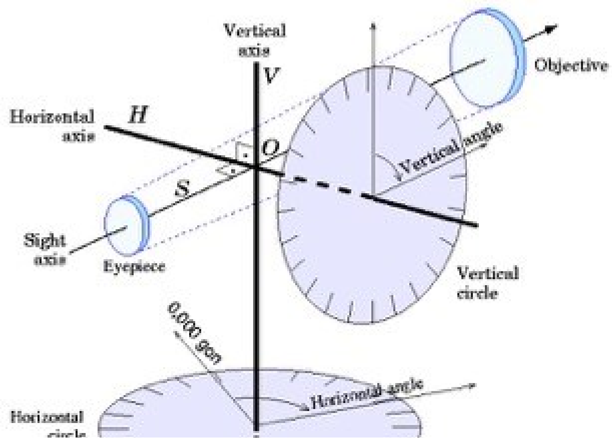

Figure 12-1: A schematic representation of a theodolite's axes and circles (http://en.wikipedia.org/wiki/Theodolite).

In maritime archaeology, the first use of a total station to record large ship structures was pioneered by Christian Lemée in 1996 during the excavation of renaissance ships at the B&W site in Christianshavn (Lemée 1999).

However, the total station has been used and is still used as monitoring device for archaeological ships such as the *Vasa* since 2000, and since recently and the *Mary-Rose*, in order to track and to understand structural deformation processes.

The *Vasa* example

Since October 2000, the *Vasa* has been monitored using a total station. Measurements are recorded twice a year, in the spring and autumn. A total of 350 target points are positioned on the outside of the hull and 50 on the inside. Every measurement is set inside a local coordinate system made of a number reference points mounted on the walls of the museum. This system till now has provided accurate measurements of the deformation of the *Vasa*, showing movements of less than 1 mm (reference).

3.2. Initial plan and technical issues

Based on previous experiences on the use of the total station as monitoring device and, especially, on the *Vasa* experience, an initial methodology and workflow was planned for this STSM. On the other hand, an innovative combination was adopted for the hardware-software set up (see paragraph 3.3.).

As for the *Vasa*, the initial plan included the positioning of target points both on the outside and the inside of the hull as well as the positioning of datum points for the referencing system on the surrounding building.

Subsequently, in the acquisition phase each target point on the hull was meant to be measured from at least two different recording positions in order to increase the accuracy of the measurement and to minimize the risk of faulty readings. However, both technical issues and concerns regarding the conservation of the ship, lead to a different approach.

The positioning of target points on the Cog meant an invasive action on the archaeological timbers. The targets would have consisted of retro-reflective tape which should have been glued on the timbers. Because of this reason, together with the fact that this system has not been chosen yet as the final method for the monitoring of the Cog, in accordance with the conservator Amandine Colson, this approach was abandoned.

Furthermore, the ship is supported by 24 metal supports close together fixed on frames. Ropes and cables also supporting the Ship from the upper part, and two platforms are constructed on top. These structures together with the structural design of the hall where the Cog is exhibited creates serious impediment for sighting target points according to the positioning of the Total station. As consequence, the plan of measuring the target points from at least two recording positions was abandoned because of the impossibility of acquiring the same points from two significant different positions. Given these limitations, a new methodology was designed during the STSM.

3.3. Hardware and software

As already mentioned, if the concept and methodology of using the total station for monitoring archaeological ships is not new, however the hardware-software set up for this project introduces a new element in the workflow.
This consist in a so called "real time" data acquisition through a software which enables a direct communication between the total station and a computer, allowing instantaneous visualization of the data acquired.
Such set-up differs from the usual workflow with a total station. Indeed, the process of data acquisition is carried out with the only help of the total station that can store the data on an internal memory. However, such procedure does not allow the user to have any visual feedback or control on the data until after the post-processing phase. As follow, both hardware and software used are described:

a. Total station: Leica TS06

The core of this STSM lies in the use of the Total station as monitoring device, thus a Total station is needed. The host institution already possesses a total station which is also one of the reason for the choosing this methodology for the COSCH project. The total station is a Flexline TS06 by Leica Geosystems, designed for mid-range applications (figure 2).

The TS06 has several different EDM modes in two main categories, all based on phase comparison of visible red laser light, but of different duration and accuracy. The main category relate to the use of reflectors with different intensity and spread of the emitted beam. Four modes are available for use with reflectors, from fine with an accuracy of ±1.5 mm + 2 ppm and a duration of 2.4 seconds to track, accurate to ±3 mm + 2 ppm but taking less than 0.15 seconds per measurement. Depending on meteorological conditions and the type of reflector used, these modes may reach distances up to 3500 m. The reflectorless modes offer a similar variation, from ±2 mm + 2 ppm accuracy with a duration of 3 seconds in standard, to an accuracy of ±5 mm + 3 ppm in 0.25 seconds in track mode. The range is normally reduced to between 200 and 1000 m.

Since the total station measures both distances and angles, angular precision differs from linear precision. The TS06 is certified to a maximum angular standard deviation of 5", or 0.00135º. In practical terms, the relationship between angular and linear precisions of 5″ is equivalent to an error of 2.5 mm at a sighting distance of 100 m. Instead, the display resolution is 0.1".

Figure 12-2: Leica TS06 (http://www.leica-geosystems.com/en/Leica-FlexLine-TS06plus_99088.htm).

The telescope magnification of the TS06 is 30x and the focusing range is from 1.7 m to infinity. Two Lithium-Ion batteries are provided which let the total station to run for approximately 20 hours. The TS06 has an internal memory that allows to store 60000 measurements. The device is also provided with a serial communication port (Baudrate 1200 to 115200), as well as USB Type A and mini B ports, and Bluetooth Wireless for transfer the data to a PC.

Errors

Total station recording is subject to a number of different error sources affecting the result in different ways. These errors can be been divided into systematic errors and random errors.

Systematic errors are errors of accuracy which act consistently on observations, and include calibration of the instrument, correction for atmospheric conditions and other such identifiable influences. In spite of this, they are consistent and thus do not interfere with data precision, as well as they cannot be eradicated through repeated or redundant measurements (Hyttel 2011).

Random errors are not consistent and include the limitations of the instrument, but also the operator, and can be regarded as errors of precision since they are the reason observations are never completely repeatable (Bannister et al. 1992). Some of these errors can be avoided by proper instrument maintenance, calibration, and operation.

As already mentioned, the novelty in the methodology for this project is in the software setting. Traditionally, the recorded data with total station are visualised in the post-processing phase. Instead, with the approach used during this STSM, it has been possible to follow in real-time the acquisition of the data. Such workflow has a series of advantages otherwise not achievable with the traditional methodology. The core lays in the use of a 3D CAD software which can communicate directly with the total station through a specifically designed plug-in. Such software is Rhinoceros 3D (figure 3) and the plug-in Termite developed by Frederick Hyttel, a former student of the Maritime Archaeology Programme in Esbjerg (University of Southern Denmark).

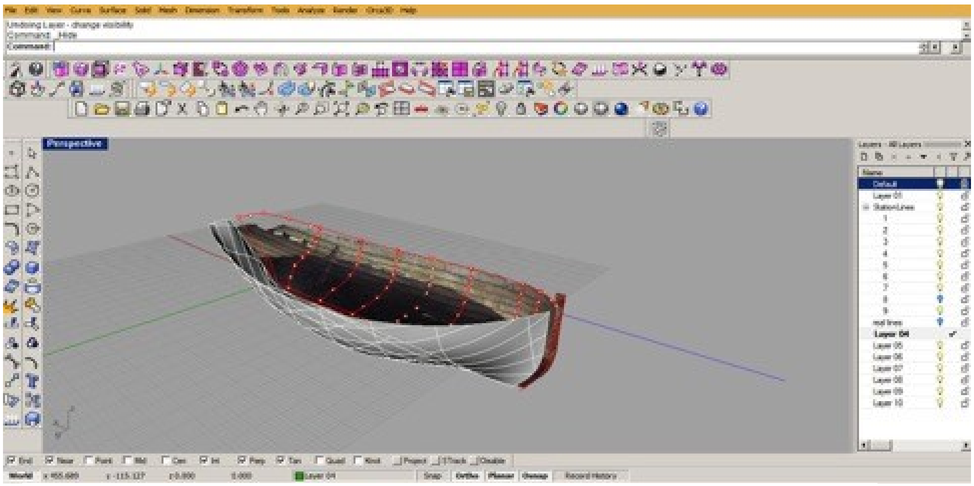

Figure 12-3: Working space in Rhinoceros 4 (Ditta 2015).

While Rhinoceros is perhaps not the appropriate CAD package for every purpose, its comparatively modest €995 offer the ideal combination for maritime archaeology: it is inexpensive, it is easy to use, and it handles two- and three-dimensional curvature exceptionally well (Hocker 2003), as well as points. Although Rhinoceros has been widely adopted by maritime archaeologists in Europe and around the world (Maarleveld 2009; Fawsitt and Falck 2011), not least because of its direct support for various digitising arms, it has also received sporadic criticism.

Termite was conceived as a means of easing the operation, and reducing the cost, of real-time connectivity between total station and CAD software for application in maritime archaeology (Hyttel 2011). To achieve this aim, it has as a core feature the ability to instantly visualise and orientate data in Rhinoceros, and secondarily facilitates easy access to appropriate total station features, while naturally retaining all of Rhinoceros CAD capabilities. The programme is compiled as a Rhinoceros plug-in against the .NET 2.0 framework and accepts Leica's GSI 16-bit data format as total station input.

The plug-in is freely available from http://www.termite-for-rhino.com, and consists of a single small file. No installation is required; double-clicking the file will open Rhinoceros and load the plug-in for use, as well as adding it to the list of items to be loaded automatically in the future. Rhinoceros may hereafter be started as normally.

Since Termite runs entirely inside the Rhinoceros framework, there are no particular requirements for software or hardware platforms to consider, as long as Rhinoceros has been updated to version 4.0 service release 7 or higher, and the system has a way of connecting the total station. Termite is however only available for the fully supported Windows version.

Termite accepts RS232 serial connections in a number of different manifestations. Since most modern computers are equipped with USB ports, the natural choice is to use either a standard Leica serial cable with a USB adaptor, or a Leica USB cable. Alternatively, connection may be established wireless with Leica's serial Bluetooth adaptor. All options are recognised by Windows and Termite as serial ports, and the choice does not affect performance or settings. Each connection type will however require its own set of drivers to function (Hyttel 2011).

The advantage of real-time visualisation of data has two direct benefits: cleaner data and a greatly reduced necessity for post-processing. Because invalid points are already corrected and new points can be named and assigned to a layer, there is simply less cleaning and patching to do. And if the data is already organised to a satisfactory standard, post-processing can almost be considered a mere matter of designing output layouts.

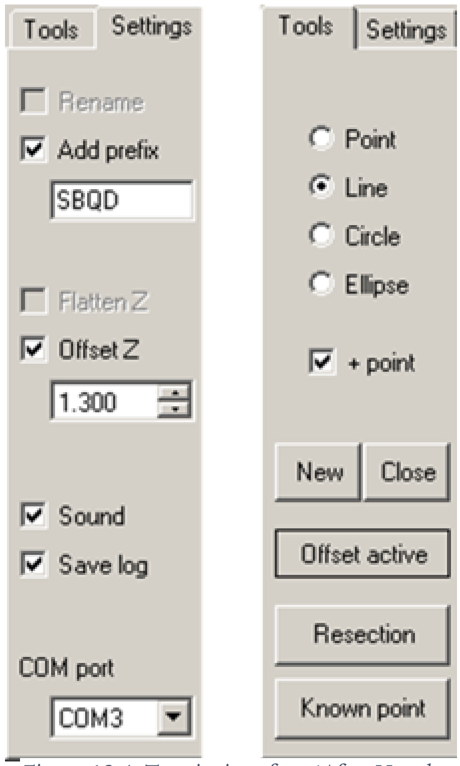

Figure 12-4: Termite interface (After Hyttel 2011).

Nevertheless, the most useful feature of Termite for this project is the ability to change position on the fly. The most troublesome aspect of total station recording is the necessity to record objects from more than one position, or station, in order to capture all relevant data. There are several ways to come around this limitations such as record data for each station as a separate file. Instead, Termite allows to record in only one model, and one file, and then to keep that file up-to-date with the total station's location and orientation. That way, the digital model will grow exactly as if the total station had never moved and the above disadvantages are avoided, while also keeping track of the accuracy of the fit between the different parts of the recording (Hyttel 2011).

The Orientate feature in Termite aligns Rhinoceros with the position and rotation of the total station, by referencing measurements between the physical control network (reference points) and the digitally recorded network (target points). The feature therefore obviously requires a control network that have to be recorded. The total station will still consider itself at the centre of the coordinate system, and it is left up to Termite to translate the coordinate data based on the instrument's calculated new position (Hyttel 2011).

The method is known among surveyors as a resection, and is characterised by yielding the coordinates of an occupied station based on horizontal bearings to three points of known position (Bannister et al. 1992) and it uses only angular data. For trigonometrical reasons, suitable reference points:

1. do not all lie on, or close to, a straight line (Bannister et al. 1992).
2. do not locate the new station on, or near, the circle described by the three control points (Howard 2007).
3. should ideally locate the new station inside, and close to the centre of, a well-conditioned triangle (Howard 2007).

The particular formula used in the software is named after J. M. Tienstra, professor at the Technical University at Delft in the early twentieth century, but has certainly be known since at least 1889 (Howard 2007). However, the Tienstra method has no inherent means of quality control. Inconsistencies in the input data will not be noticed since there is no redundancy, and the algorithm will always give simply a coordinate with no indication of its accuracy.

To enable some degree of verification, Termite uses a technique described by the US Army (1993, chapter 6.5). Using a fourth control point (figure 5), the entire orientation procedure is repeated with this check point and the second and third control point, forming a new triangle which partly overlaps the primary triangle. This second resection will offer an inevitably slightly different result for the position of station P, and the three-dimensional distance between the two positions thus gives an indication of the correspondence between the two resections (Hyttel 2011). Since the two positions are very unlikely to yield similar erroneous results, a shorter distance is likely to indicate a more accurate orientation. The distance itself is reported as a radial error (E) in absolute terms, and relative to the size of the control network as an accuracy ratio (R) from the calculation. Although the accuracy ratio clearly does express a ratio, Termite reports the value as a percentage (Hyttel 2011).

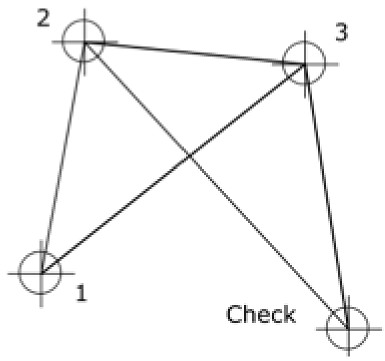

Figure 12-5: Overlapping triangles of two resections between four control points (after Hyttel 2011).

Since the accuracy of the orientation process literally sets the maximum for achievable accuracy in any subsequent measurement, knowing what quality to expect is clearly important. While the limitations of the instrument naturally play a dominant part, the tolerances of the resection algorithm and not least the destructive influence of the human element are more difficult to gauge (Hyttel 2011).

To conclude, in order to run Rhinoceros/Termite for the recording phase, it has been used a netbook Asus (figure 6) equipped with an external re-chargeable battery, property of the Maritime Archaeology Programme University of Southern Denmark. The tested autonomy for the PC/battery system is over 12 hours.

Figure 12-6: Example of the working set-up. The total station connected to the portable PC (Ditta 2015).

3.4. The new plan and workflow

a. Reference points

Considering the limitations explained in the paragraph 3.2., during the course of this project a new plan has been formulated and applied. For the setting up of the monitoring workflow two sets of data are needed: 1) reference points; 2) target points. As already explained in the previous paragraph, the network of reference points is necessary for establishing the positions of the total station and the subsequent resections, as well as to continue the monitoring over time. The present STSM had the advantage of being the last in the series of monitoring test projects and a number of reference points were already in position in the surrounding structures of the exhibition hall. However, since the resection methodology used by Termite requires a network of 4 points for each station in which the total station should be place in, new reference points were placed in addition of the pre-existing ones. This allowed a better coverage of the referencing network and avoided blank spots due to visual obstruction given by both the ship and other structures. New reference points were placed at each floor of the exhibition hall. The positioning was planned a manner that from the first recording position a new set of reference points was in sight to be acquired. Moreover, to add redundancy and practicalness, from each station more than 4 reference points are visible. Therefore, allowing a more flexible repositioning of the total station in accordance with the need and preferences of the surveyor. The reference point network consists of a total of 47 points, of which 28 used already for the photogrammetry and the 3D scan and 19 newly added.

Figure 12-7: Example of reference points (Ditta 2015).

b. Target points

With a defined referencing network, the next step was to define the target point network for the actual monitoring of the ship. For the reasons mentioned in the paragraph 3.2, the target points were selected according to different criteria to provide sufficient information for the monitoring. Two main types of target points were selected: marked points and "timber feature" points.

On the outer hull of the Cog, a series of paper and plastic coded targets (figures 8 and 9) are visible. These targets were fixed on the outer strakes and construction elements of the Cog over the years starting in 2007 for a 3D scan. During the early first week of the project, an evaluation of the strength of these points was done which established the number of reliable points and also the areas not sufficiently covered by these points.

Figure 12-8: Example of paper coded target (Ditta 2015).

The paper coded targets are marked with a 3 digit id number (e.g. 123) while the plastic targets are marked with the letter U followed by a 2 or 3 digit number (e.g, u92 or u101). In the recording phase, to each marked target point was assigned a corresponding id number in Termite. However, in several cases, the plastic targets are missing an id code (figure 10). To overcome this issue and to provide a code which allows an easy identification of the point, to these unidentified points was provided a code related to the closest paper coded target and the direction from it. For instance: Looking at the unidentified point, the closest marked point is numbered 200 and its position is under the marked point. Thus, the code for the unmarked is 200D, where D stands for down. Such id system was adopted because it consents to find the point n and then to look at the direction code to identify the point 200D. The other direction codes are: L= left; R= right; U= up.

Figure 12-9: Example of plastic coded target (Ditta 2015).

Nevertheless, some areas of the outer hull and the whole interior of the Cog are completely missing of marked targets. To overcome such lack and to avoid the addition of physical targets, the following strategy has been used. The timbers of the Cog are often jointed together with nail heads, bolt heads or other joinery elements (figure 11).

These features provide a “natural” marker since can be easily centred while aiming with the total station. Such unmarked points were defined as “timber feature” points and recorded in Termite with the id T followed by a 3 digit number (e.g. T100). Compared with the marked points, these points are not easily recognizable given the great number available of timber features. For this reason, every time a suitable “timber feature” point was identified, a catalogue entry was created. The catalogue consists of a photograph for each point lit up by the laser beam from the total station together with a description of the type of point and its surrounding, for an easier recognition. Fundamentally, the photograph provides the generic position of the point in comparison with the overall structure, while the description allows to exactly pin the point.

Figure 12-10: Example of unidentified plastic target (Ditta 2015).

The marked points provide information for the outer hull of the cog, from the turn of the bilge to the upper structures as well as for the outer part of the stern and stem post, both for the starboard and portside. Whereas, the “timber feature” points on the outer hull are mostly concentrated at the bow, at the stern, and at the aft on the portside. Instead, the interior “timber feature” points cover information for the bottom strake and frames of the Cog, as well as for the beams, breasthooks and stranding structures for the aft castle.

Figure 12-11: A "timber feature" point lit up by the laser point of the total station. In this case, the point is the centre of the wooden peg (Ditta 2015).

To sum up, a total of 196 target points were identified and recorded (figures 12, 13, and 14), of which:
- 144 on the outer hull: 118 marked; 26 “timber features”.
- 52 on the inside of the ship, all “timber features” points.

Figure 12-12: Side view of the target point cloud (Ditta 2015).

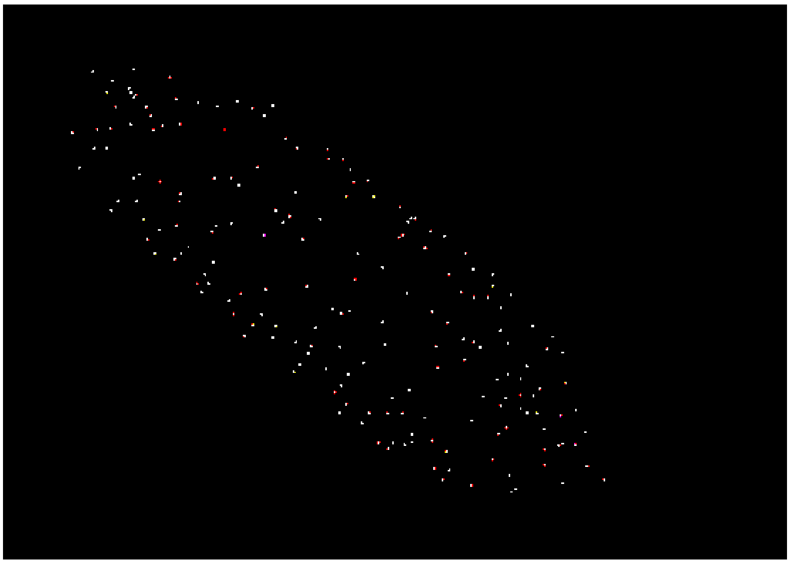

Figure 12-13: Top view of the target point cloud (Ditta 2015).

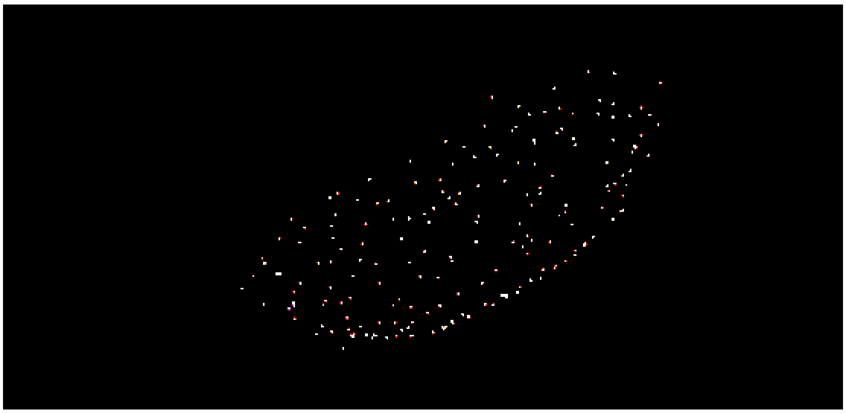

Figure 12-14: Perspective view of the target point cloud (Ditta 2015).

c. Recording stations

With the established reference and target networks, the final step was the identification of the most suitable stations for the positioning of the total station. The main requirements are essentially 2: a clear sight of at least 4 reference points, and a visual contact between the target or reference points and the total station aiming cross between 90° and 45° angle. The angle range limit was decided to avoid too oblique aiming which could increase the chance of errors. Thus, it was preferred to maintain an almost parallel line of sight between total station and the target points. These two requirements had also to be mitigated with the shape of the ship, the hall structures, and the supporting structures for the Cog.
A total of 22 recording stations were identified and used for the recording phase. The stations are dived as it follows (figure 15):

- 16 stations on the ground floor: 7 for the starboard, 7 for the portside and 1 position each for the bow and stern;
- 2 stations on the 1st floor at the starboard side towards the interior;
- 4 stations on the 2nd floor: 2 at the starboard side and 2 at the portside.

In Rhino, a layer for each station was created in which were recorded the target points visible from that position. The system enables a degree of flexibility, since for each station only a given number of target points and reference points are visible. With this information, the surveyor can establish the most suitable way to position the total station according to his needs. The stations at the ground floor, were used only to record target points on the outer hull, while the remaining positions were used for the recording of the interior target points. On the 1st floor, only two recording position were established for the instability of the balcony platform. The stations are situated at the corners of the balcony structure where the structure is more stable, and vibrations produced by walking on the structure cannot affect the total station. The impossibility of stable readings taken from the middle of the balcony, lead to plan 4 more stations on the 2nd floor.

The recording of both reference and target points was carried out with the Leica TS06 in reflectorless mode set to fine, thus with a linear accuracy of ±2 mm + 2 ppm at 200 m.

The length for the present STSM project was 21 days, divided as it follows:
- 2 days for the re-planning phase;
- 14 days for the recording phase;
- 5 days for the checking and post-processing phase.

Figure 12-15: Map for the position of the recording station (Ditta 2015).

4. Description of the main results obtained

4.1. Potential Errors

The final result of the present project is a 176KB Rhinoceros file, which includes layers for each station and related target points acquired from that position, and layers for the referencing network, divided by floors. Regarding the accuracy of the approach, some considerations can be drawn. The recording setting of the Leica TS06 established the minimum linear accuracy achievable. However, another factor to be taken in consideration is the angular error that for the Leica TS06 is of 5”. While the distance accuracy remains nearly constant for measurements out to around 200 m, the angular accuracy must decrease significantly with increased distance. The maximum operative distance between the total station and points was less than 25 m, thus a bit of trigonometry reveals that the 5” angular accuracy has fanned out to a maximum linear error of 0.6 mm. At any rate, the linear accuracy of the recording mode should be considered as a systematic error which acts consistently on observations. Therefore, it does not interfere with data precision, as well as it cannot be eradicated through repeated or redundant measurements. On the contrary, the angular accuracy does not have the same properties. Due to its linear variation in relation to the distance between the total station and the target, a fluctuation of values is inevitable. Thus, such fluctuation must be considered as a measurement noise.

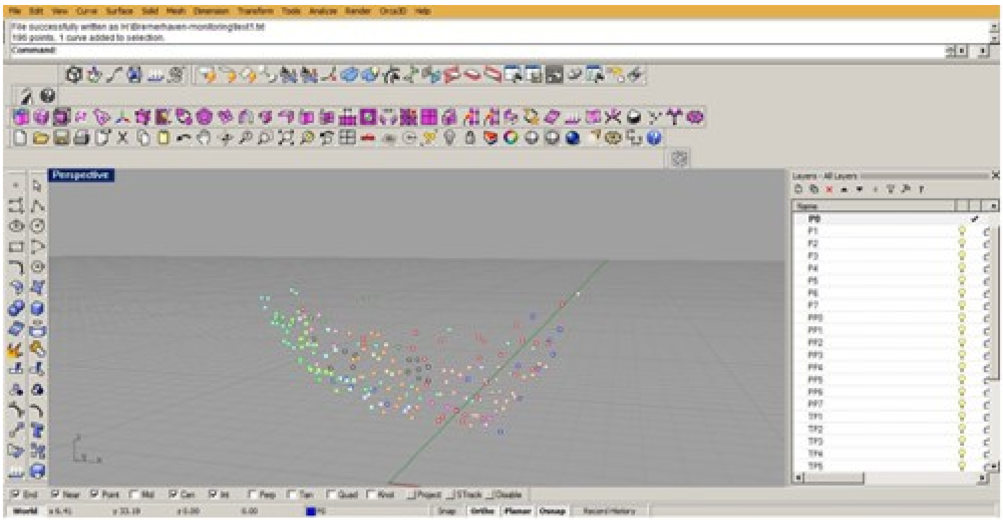

Figure 12-16: The final result as visualised in the workspace of Rhinoceros (Ditta 2015).

Another source of errors must be identified in the resection process. Any recorded point is subject to what might be called an accuracy inheritance, in the sense that no point can be more accurate than the accuracy of the station from which it was recorded (Hyttel 2011). Errors are always cumulative in such a hierarchy, so the accuracy of a recorded point is the combined error of both reference points, the station position and the detail measurement. For every such step, a certain dilution of accuracy is inevitable (Eiteljorg 2002). Ideally to ensure optimal accuracy, the points for the reference network should, if at all possible, be recorded at the same time from the same station (Andrews et al. 2009, 10), and on-the-fly reference points added only where site layout unavoidably dictates. However, because of the layout of the exhibition hall, the acquisition of all the reference points was done from 4 different stations. From the first station, the total station was moved and resectioned to the successive station and so forth.

This approach obviously added additional errors to the reference points acquired in the successive stations. To mitigate this disadvantage, the resection was carried out several time, till finding the optimal resection with the lowest error ratio. If the minimum accuracy required of archaeological documentation is considered somewhere around 1:1000, or 0.1% (Bowden 1999), in our case the accuracy ratios for the positioning of these stations ranged between 0.0009% and 0.0024%. However, given the fact the reference network is not to be recorded again in the successive monitoring missions which will use this methodology, these added errors due to the resection process must be considered as systematic errors and thus redundant and not affecting the final results. Ideally, the referencing network will remain in place and using the same file for the subsequent acquisitions, no errors will be added to the existing network.
For the recording of the target points, the resection accuracy acts as measurement noise. Indeed, every time the total station is moved to the next recording station, the resection is performed with a specific constant error to target points for the given station. As for the referencing network, the resection was performed with the best accuracy possible. The resection accuracy values range from 0.0009% to a maximum of 0.0094%, well beyond the standard for archaeological documentation. To understand how much the resection could affect the accuracy of the data, a test was carried out. The total station was moved twice in the same station area with a slightly different positioning. The value for the resection accuracy from point A to B was of 0.0066%, and the same target points were recorded from both positions. The maximum difference between the coordinates of two points was ±0.03 mm, far beyond the total station's own certified accuracy. Therefore, it can be stated that taking into account both the resection and the angular errors, the measurement noise is expected to fall well below 1 mm.

4.2. Reproducibility of the protocol

The time spent to perform the present project does not truly reveal the real length of this monitoring methodology. As explained in the paragraphs 3.4., several days were spent for the new planning phase and during the recording phase, time was spent to establish the optimal station position and resection setting. As a result, with an established protocol it could be possible to perform the only recording phase in less than 16 working hours.

Moreover, the user-friendliness of this methodology supported by a guideline for the procedure will let the surveyor to perform a straight forward acquisition with a minimum training. The only limitation is due to the "timber feature" points. If the target points on the hull are easily recognized because are clearly marked, the same cannot be said for the "timber feature" points. For this reason not only the catalogue of these point is necessary, but also a minimum of knowledge in ship construction and its terminology is required from the surveyor. Indeed, the catalogue is compiled according to the English technical terminology that applies to ship structures which is univocal and internationally accepted.

The possibility of exporting the Rhinoceros file in several formats, proprietary and open formats, allows an easy interexchange of data as well as data sustainability. For these reasons, even though the host institution owns a valid license for Rhinoceros 4, besides the proprietary format of Rhinoceros (.3dm) the file has also been saved in the following formats: .obj; .txt; .csv; .dxf.

4.3. Preliminary deformation assessment

Compared to photogrammetry and 3D scanning, the present methodology produces a limited amount of data. Instead of having a cloud of points for the entire ship, only a limited amount of points are recorded and can be constantly monitored. To understand the deformation processes acting on the Cog, the functionality of Rhinoceros can be exploited to compare different acquisitions in the same working space. Although the next total station acquisition will be carried out in the next 6 months, and therefore no data for comparison are available yet, a preliminary deformation assessment was performed. In order to show the advantage of using Rhino not only as recording software but also as analysis software, the shape of some elements of the ship were analysed through curvature analysis. A selected number of points at the same level were connected for three strakes at the starboard side, a bottom breadth section at amidships, and a portion of the sheer of the keel. The curvature analysis visually display in an exaggerated scale the curvature trends, and thus it allows to understand where forces are acting.

From the figure 17, it is possible to notice that the upper strake on the starboard side is deformed and the curvature is not fair. Moreover, it seems that at the extremities are tending towards the outside while the central part is tending towards the inside. The same can be said for the bottom breadth section (figure 18), were the curves at the bilge are tending outward while close to the keel are tending inwards. The keel is also having this outward/inward tendency. Such heavy outward/inward tendencies are not common in ship shapes, therefore they underline deformities in the structure which are not typical for "healthy" ships. However, at the moment it is not possible to state if they are the result of ongoing process or if such deformities reached stability. Only further monitoring mission can shed light on these questions.

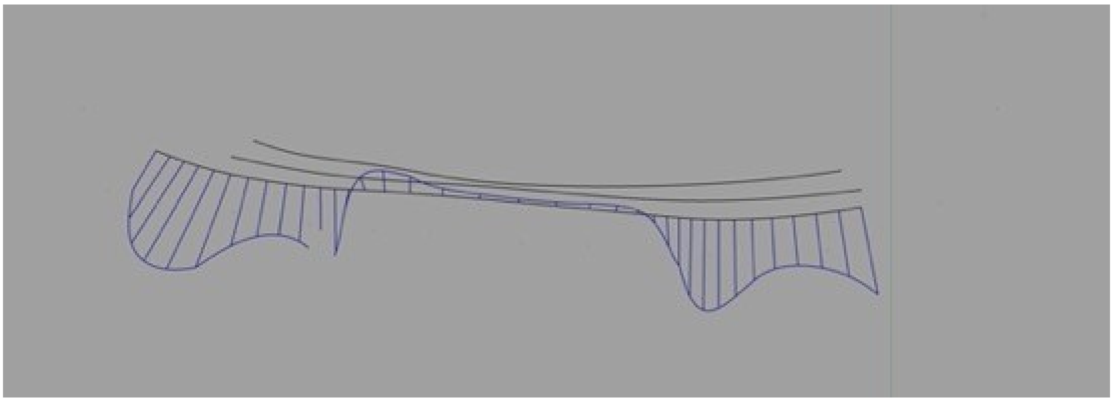

Figure 12-17: Curvature analysis for the curve of the upper strake (Ditta 2015).

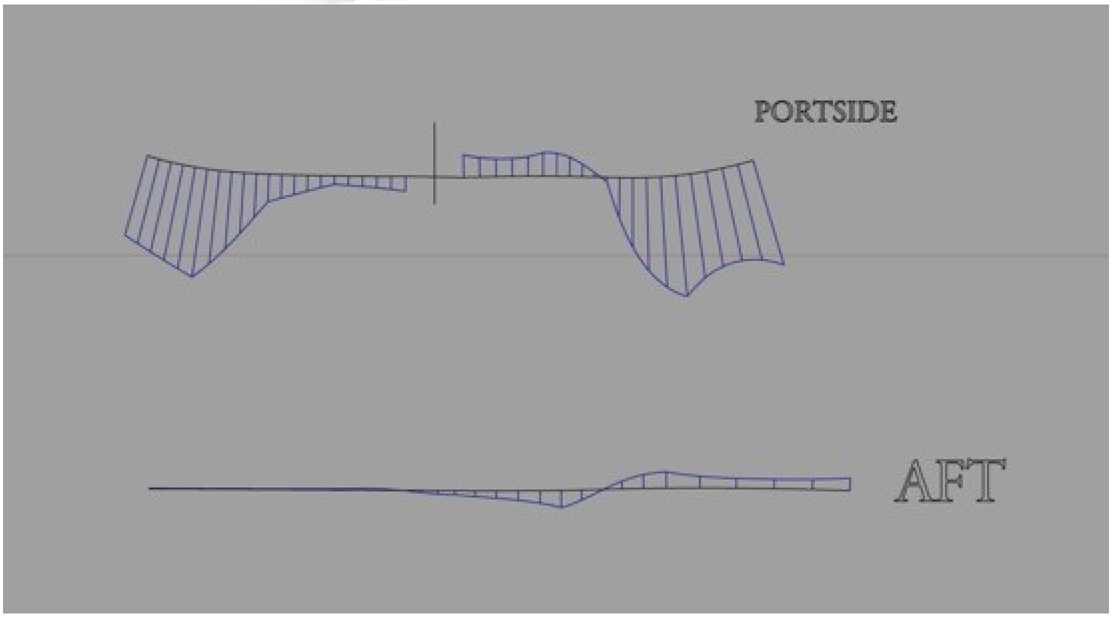

Figure 12-18: On top: curvature analysis of the breadth section for the bottom of the hull; Below: curvature analysis of a sheer of the keel (Ditta 2015).

5. Future research including collaborations with host institutions

In spite of the simplicity of the system and the user-friendliness of Rhino/Termite, it seems obvious that the end-users must be trained on a basic level to be able to understand the process but also to be able to conduct an acquisition themselves. In order to establish a reproducible protocol, a guideline with a step-by-step description is been written by the author of this report. The guideline includes the set-up, a catalogue with the description of the point and useful tips for repeating the monitoring.
Moreover, further work together with the conservator to analyse the results is necessary, perhaps through another STSM.

6. Projected publications/Articles resulting or to from the STSM

Amandine Colson reported about the present work at the Condition 2015, 19-22 May in Gdansk, Poland - Conference about conservation and digitization of cultural heritage objects. Supported by Norwegian funds.
In 2016, Amandine Colson will present these results at the Conference of Wet Organic Archaeological Material Group (WOAM) from the International Council of Museums - Committee for Conservation (ICOM-CC) in Florence.
Additionally, the results of this STSM will be presented for the new exhibition of the *Bremen Cog*, which is opening to the public in spring 2016.

7. Confirmation by the host of the successful execution of the mission

We confirm that Massimiliano Ditta, worked at the Deutsches Schiffahrtsmuseum from 07/04/2015 to 28/04/2015.

The mission was very successful and the results very promising. This collaboration and moreover the fact that the museum was fully involved in the process was very inspiring for future projects. Massimiliano Ditta was taking part in some internal meetings about the future of the exhibition and provided his expertise.

Documentation of large scale historical or archaeological artefacts is not an easy task and monitoring them for long term research is also very challenging. Therefore we are very thankful to Massimiliano Ditta and the COSCH network for the excellent work that has been accomplished.

We are looking forward to present the results to our colleagues during the next COSCH Meeting.

Amandine COLSON, M.A. Conservator at the Deutsches Schiffahrtsmuseum

Dr. Ursula Warnke, Director at the Deutsches Schiffahrtsmuseum

8. Financial summary

Travelling expenses: train from Brørup St. to Bremenhaven Hbf and return (88€ x 2 = 176 €)
Accommodation: supported by the museum
Daily expenses: 45€ per day x 21 days = 945€

- Breakfast: 21 x 10€
- Lunch: 21 x 15€
- Dinner: 21 x 20€

Budget available: 109€

9. Potential interdisciplinary value of research carried out and any other comments

Besides fixing a benchmark for further monitoring missions employing a total station, the output of the present project can be used for comparing different monitoring methods. For instance, it could be used for Comparing data with the ones produced with photogrammetry and 3D scanning recording. Furthermore, it could help to find solutions for methodological issues: which technique is the most pertinent, how these two techniques do could complete each other.

It must be noted that the choice for the referencing network and target points cannot be considered optimal. The referencing network is made of removable A4 paper markers, posing a problem of durability. However, given the flexibility of the resection in Termite, a simple solution can resolve said issue. A new network of adequate reference points (prisms or fixed reflective targets) can be positioned while the old network is still in position. The new reference points could be then acquired through resectioning the total station inside the old network. Once the acquisition is completed, the old reference network could be removed.
A similar issue affects the target points, since the coded markers are made of paper. A solution would be to place pin in the centre of the markers and then replace them with a more permanent indicators. Likewise, more permanent and visible markers could be laid on top of the “timber feature” points, which could also ease the issues related to the identification of those points.
At any rate, these possible solution should be discussed with the conservator and taken in consideration if this methodology will be systematically used by the host institution.

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Appendix D. COSCH – Report STSM – Data fusion

STSM Report

Evaluation and validation of the 3D Data from the Bremen"Cog" monitoring project - German Maritime Museum

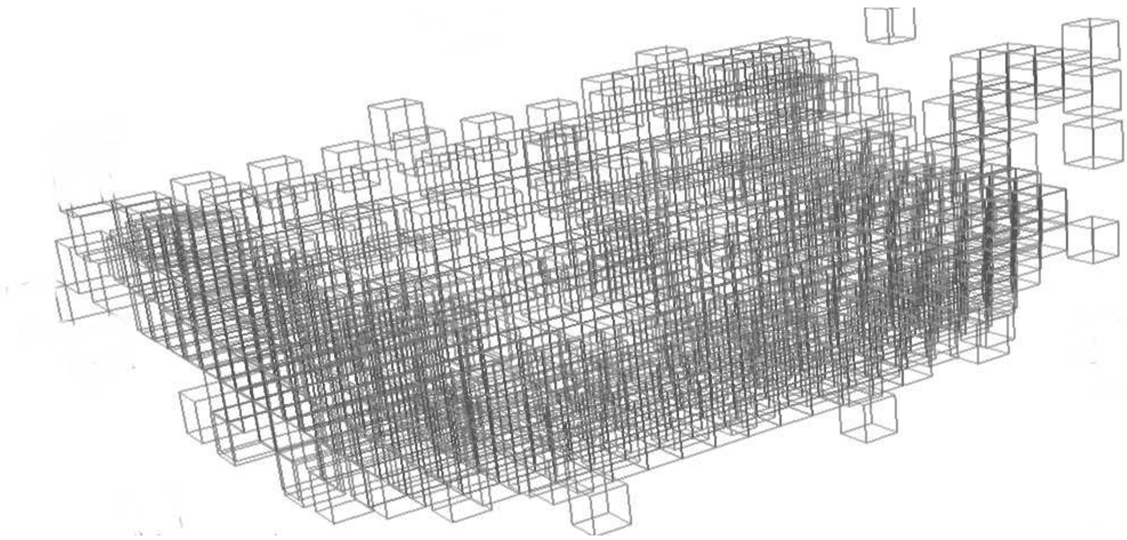
Reference: Short Term Scientific Mission, COST TD1201 - 210915-062809

Beneficiary: Levente TAMAS, Technical University of Cluj, Cluj-Napoca (RO); Levente.Tamas@aut.utcluj.ro

Host: Colson Amandine, German Maritime Museum (Deutsches Schiffahrtsmuseum), Bremerhaven, Germany; Colson@dsm.museum

Period: from 20/09/2015 to 27/09/2015

Place: German Maritime Museum (Deutsches Schiffahrtsmuseum), Bremerhaven, Germany,Bremerhaven, Germany



1. Purpose of the STSM

The main purpose of the current STSM proposal is to investigate the use of heterogeneous data inthe surface monitoring process of the Ship from the German Maritime Museum. Several types of recorded data from different epochs are available capturing this object, thus the monitoring of thesurface involves the comparison of various data sources such as lidar, RGB or RGBD data.

For the comparison purposes both linear and nonlinear alignment algorithms will be evaluated in terms of runtime, accuracy and robustness. Also at least two different approaches (e.g point basedand patch based) will be targeted in order to find the best suited method for this task.

Finally, the procedure can be described in the COSCH-KR framework as a proof of concept for thistask.

2. Contribution to the Actions objectives

One of the main tasks of COSCH WG 3: Algorithms and procedures is to find ways to integrate heterogeneous data and use this for monitoring purposes. In this specific topic during the STSM different types of depth data were used to investigate this problem including different type of laserdata, structure from motion and data acquired from projected light devices. The per-processing, registration, comparison and visualization phases fit mainly within the WG3 profile, although dueto the complexity of the problem it involves also the activities from WG1 through WG5 .

3. Description of the work carried out

The 3D spatial measurement problem represents a emerging multi-disciplinary research field. Each application requires specific data handling acquired even from the same measurement device, thus the unified handling of the is an essential task to be done in case of heterogeneous measurements.

Different sensors can be used for the data acquisition including stereo cameras, laser range finders, time-of-flight cameras, or the recently adopted structured light sensors [3]. These devices have their own special characteristics in terms of precision, range or speed. Thus the way in which these sensors are selected depends on the specific requirements of the measurement problem to be solved [4].

The large area inspection, such as the urban area measurements require several different measurements to be aligned in the same coordinate frame. This kind of problem is well studied in the 2D mainly in the image processing domain. Although these 2D algorithms can be adopted for the 3D data registration, they need special adaptation for the spatial data. Also the data characteristics such as range, noise or data distribution have large influence on the algorithms used for 3D data processing [5].

For the data merging different algorithms can be used including keypoint and feature descriptor extractors, nonlinear correspondence estimators or semi-automatized variants [6]. Although the datamerging can be performed based only on the artificial marker location information, lacking this dataother methods have to be applied [7]. Hence a more robust method is applied for the initial alignment phase based on an extracted keypoint-feature data set [8]. A similar version of this approach was also adopted for the paper at hand.

The work carried out in this STSM was linked to the main requirements presented in the previoussections and is presented in Illustration 1:

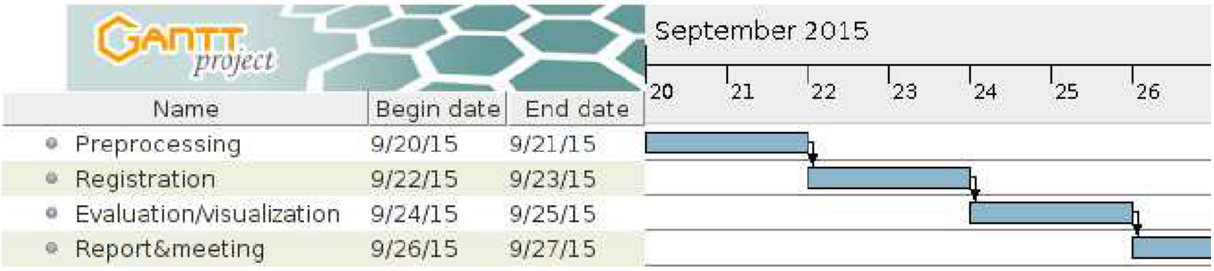


Illustration 1: Workflow

The main work phases of this STSM included:

- Preprocessing of the data in order to have all the measurements in a common coordinateframe using keypoint-feaure correspondences.
- Registration of the per-aligned data from the previous step using GICP techniques in orderto minimize the error global distance between the two models and to be have a common reference for the different data sets.
- Compare the structure of the data using octree representation ensuring the relevantdifference detection in the 3D heterogeneous data.

All the above mentioned methods were implemented in C++ using the point cloud library, thus allowing a large scale flexibility in the data manipulation and representation. The methods are general enough to be used also for other data set comparisons.
The main reason for the above mentioned work-flow was the following:

- need for alignment of data with different reference systems without knowing the relationamong these reference systems (they were recorded in different coordinate systems);
- need for custom data handling;
- need for custom data visualization;
- high amount of 3D data processing.

4. Description of the work output

The work output of the STSM can be summarized along the main topics addressed in the proposed workflow, i.e.: preprocessing, registration, evaluation, and visualization.

4.1. Preprocessing

This step included the preparation of the input data from different format in an ASCII representation, allowing the maximal compatibility to import-export for/to different formats. This was necessary, as different tools were used to acquire and save the 3D data.
Beside the common format issues, the data preprocessing included filtering task such as: voxel gridfiltering (to reduce some scan sizes up to a reasonable level in order to facilitate the fast prototyping), statistical outlier removal (for spurious point detection and removal).
After this step, the keypoint-feature descriptors were searched in the 3D data pairs. This was necessary in order to get an initial estimate to the rigid-transformation that is needed to be estimatedbetween two different scans. The fast point feature histogram (FPFH) seemed to behave robust enough in order to use in different data sets, thus this was adopted for as implementation variant.
The detected key-point features are then paired in the two different data scans in order to have an initial estimate for the point correspondences, as this is also visible in Illustration 2

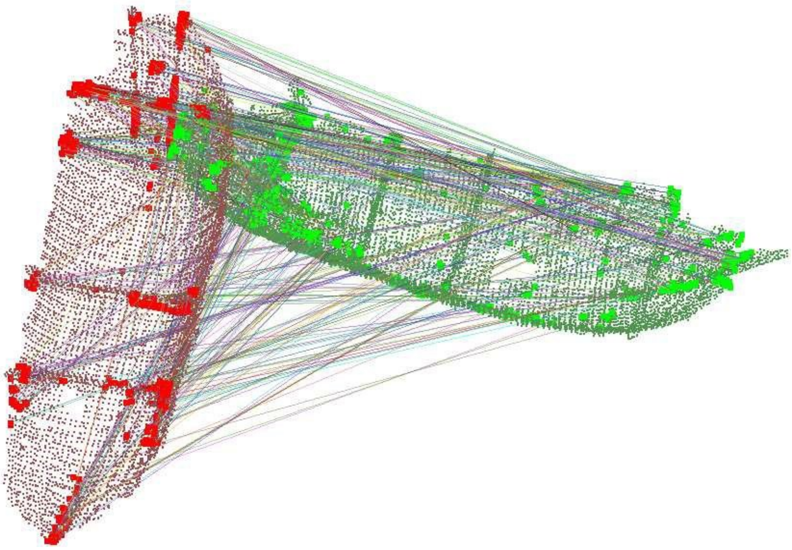


Illustration 2: Keypoint-feature based prealigment for two different laser scans

4.2. Registration

Usually, these point correspondences have also some false positives, thus these need to be filtered inorder to get a appropriate initial guess for the alignment. This was performed in the current work- flow using a sample consensus based approach. After this filtering is performed, the initial alignment can be computed, such as this is illustrated in Illustration 3.
From this initial alignment, the refinement phase of the algorithm is the next step. The initial alignment is crucial, in order to reduce the probability of ending up the fine tuning aligning in alocal minimum.

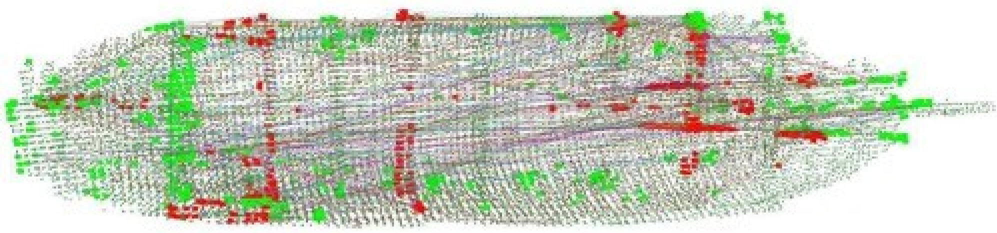


Illustration 3: Correspondence filtering for the detected keypoint-feature pairs

The summary of the proposed alignment method is presented in Illustration 4. The algorithm begins with the computation of the FPFH features both for the target and the source data. The next step is the estimation of the initial alignment using the filtered correspondences between the two set of keypoint-features. Finally, the algorithm loops while the refinement of the alignment between the two 3D data sets is not finished according to the final conditions, i.e. minimum overlap error or maximum iteration number is reached.

4.3. Comparison between different recordings

In order to analyze the the possible deformations of the ship during the time, first the laser scansfrom 2009 were compared against the dense laser scans from 2014. The procedure included the above mentioned initial alignment – refinement procedure, as well as the analysis of the aligned data.

Algorithm 1 ICP with initial alignment

Require: P_s, P_t

F_s = ComputeFPFH(P_s);
F_t = ComputeFPFH(P_t);
$(t^*, A_f) = InitialAligment(F_s, F_t)$;
while $(error_{diff} < \epsilon)$ or $(iter < iter_{max})$ **do**
  $A_d = getClosestPoints(t^*, P_s, P_t)$;
  $t^* = argmin\left(\frac{1}{|A_d|}\sum_{j \in A_d} w_j \, |t(p_s) - p_t|^2\right)$;
end while
return t^*

Illustration 4: ICP with initial alignment

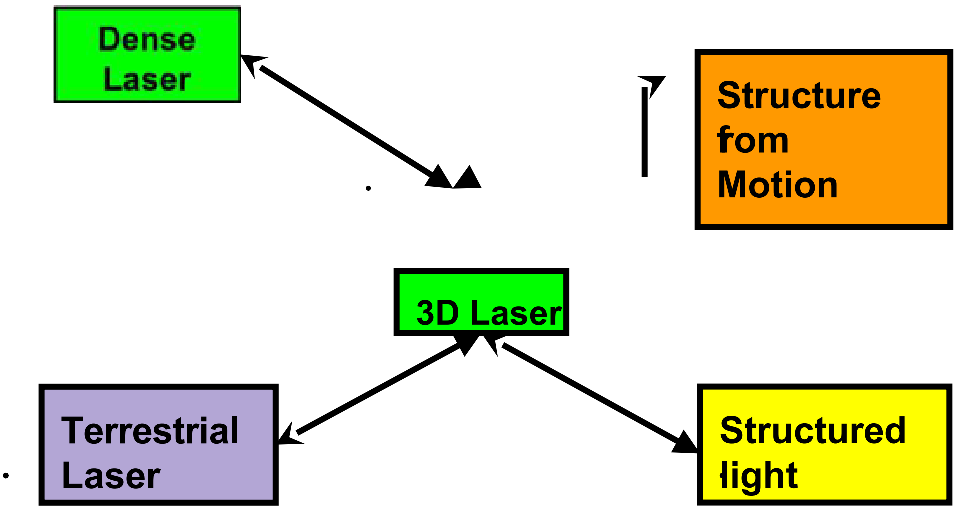


Illustration 5: Comparisons carried out

The summary of the performed comparisons are presented in Illustration 5: the reference point cloud in all cases was considered the latest 3D laser scan which already was measured with landmarks that ensured to be referenced with respect to the building.

The first alignment results are visible in Illustration 6. Although the scans from 2009 contain only the interior part of the ship and the one from 2014 contains both interior and exterior, the match quality is quite good (even though they initially were not in a common coordinate frame), showingno big scale deformation of the object, shown in Illustration 7.

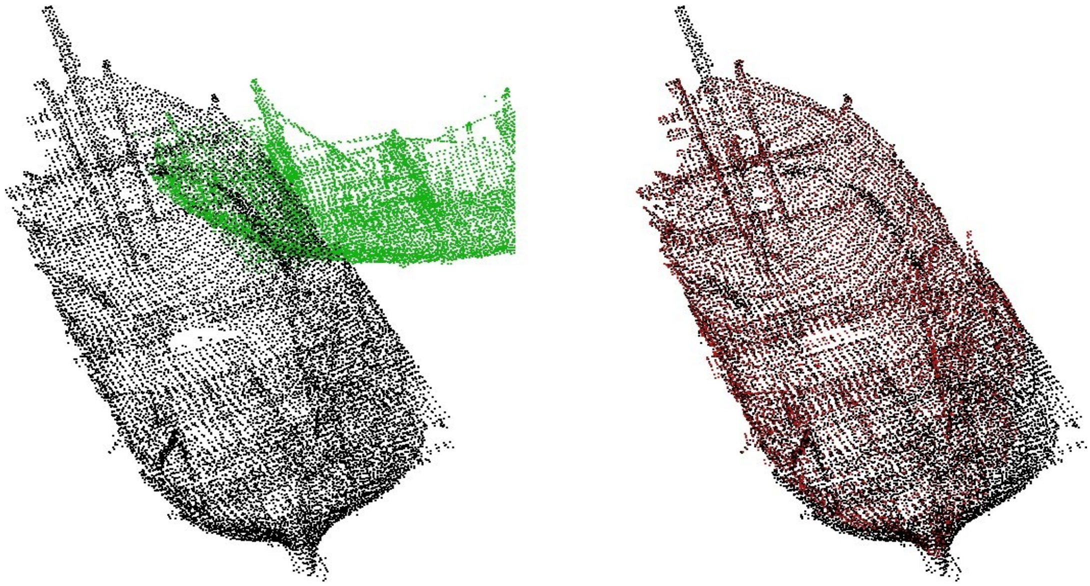


Illustration 6: Laser (i3mainz) 2014 - Laser (KSF) 2009; left hand: initial position inspace; right hand side aligned variant

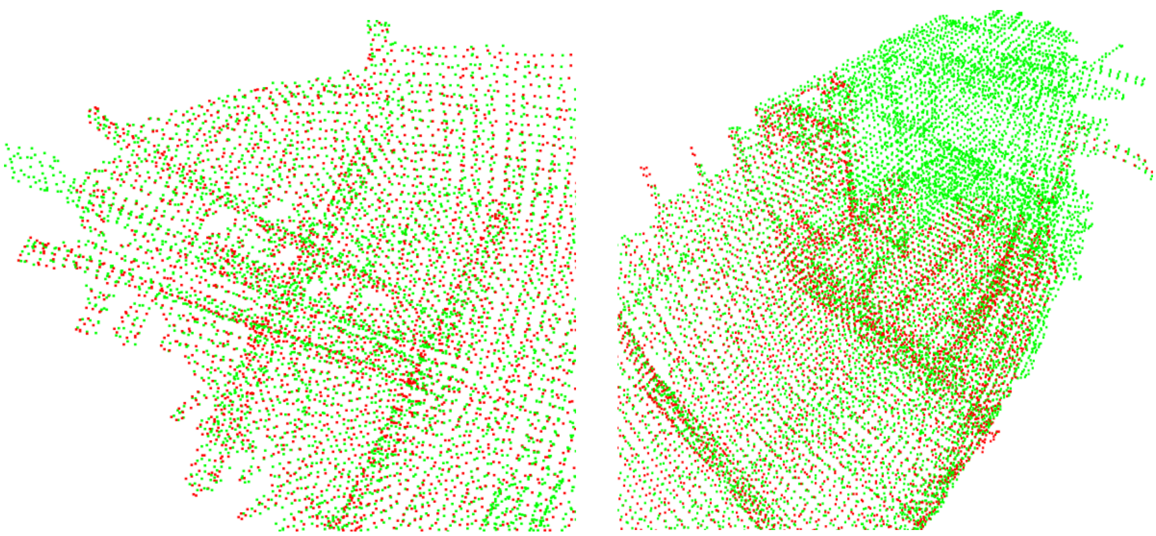


Illustration 7: Zoomed in section of the front and back ship

For a better visibility of the comparison a down sampled variant of the source-target clouds are plot, in order to have a clear picture of the final comparison 3D plots

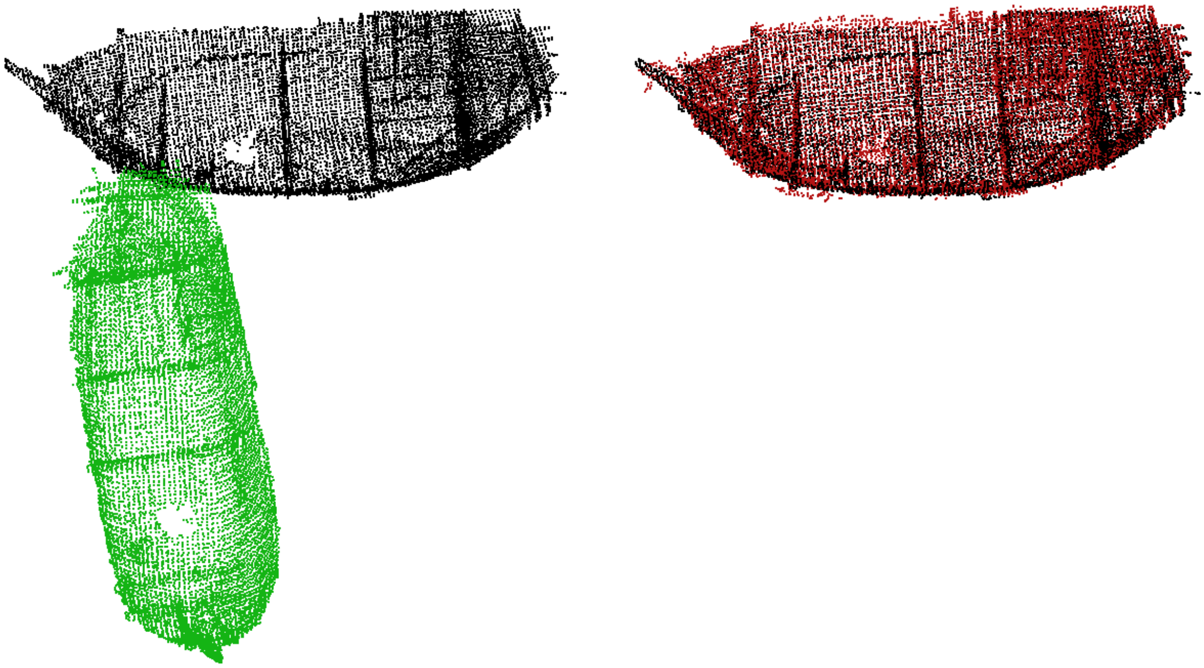


Illustration 8: Laser (i3mainz) 2014 - SfM (Captair) 2014: left hand side showingthe data in its original coordinate; at hand side with the aligned data. Details regarding the SfM measurements can be found in the STSM report of J. Guery

The second alignment was performed on laser and SfM data from the same year(STSM report of J. Guery). As it can be seen on Illustration 8, the SfM fits well the reference laser data. Moreover, no sign of large scale distortion is visible on this figure. The zoomed in front and back parts of the shipis visible in Illustration 9. The SfM is more affected by noise than the laser scan, nevertheless in thisimage sign of lateral or longitudinal larger scale distortion is not visible.
Thus, even with such a lower precision (compared to laser) measurement method, relative goodresults can be achieved, but these are not comparable to a laser scan accuracy.

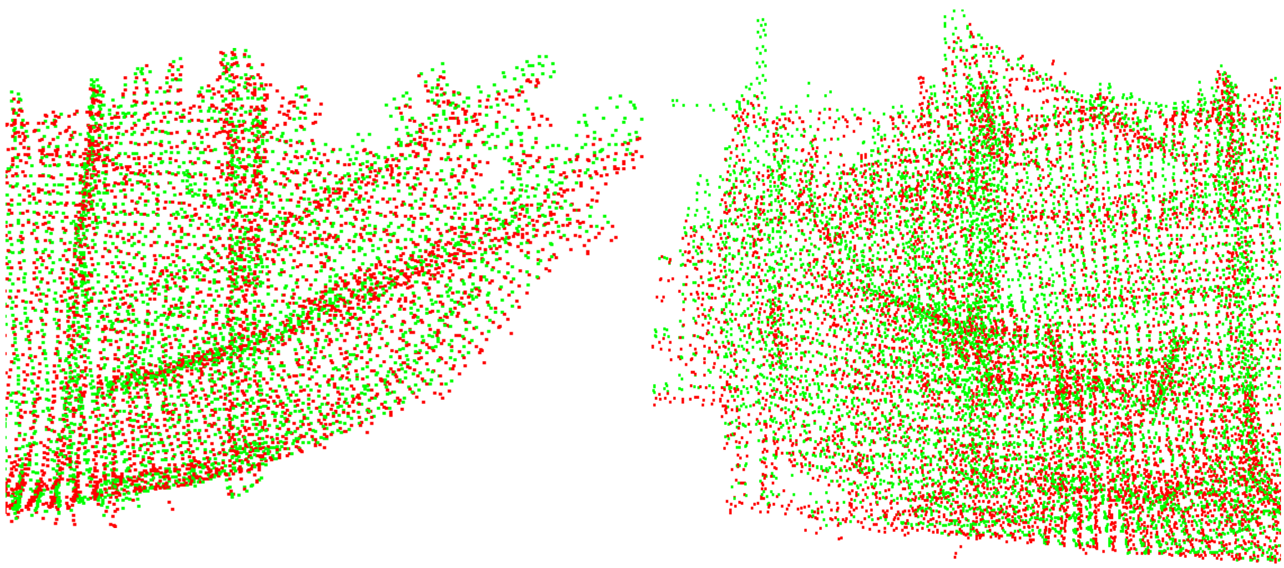


Illustration 9: Zoomed in front and back parts of the ship after the laser and SfM alignment

The third aligning was using the Laser data from 2014 and the high resolution (under millimetre precision) structured-light scan from the same year. As only a small part of the ship was scanned with the structured light scanner, without having a common reference with the laser scanning, the alignment of the scans had to be performed using the above-mentioned methods. The result of the registration is visible in Illustration 10.

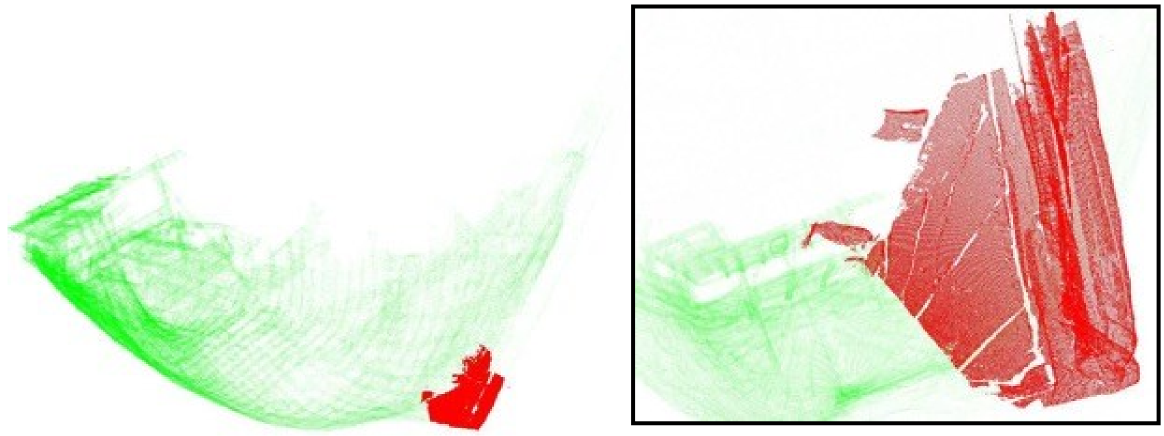


Illustration 10: Laser -- structured light registration (zoomed section on the right hand side)

4.4. Evaluation/visualization

For the evaluation three different techniques were considered: euclidean distance based one, treestructure based one and cross section analysis. These were analyzed on the largest time span dataacquisition, i.e. the laser scans from 2009 and 2014.

Euclidean distance metrics evaluation

This type of evaluation makes use of the kd-tree search algorithm in order to compare the two point clouds: for each point from the source cloud the nearest neighbour point is searched in the target point using the kd-tree searching method. The result for such a comparison is quit straightforward: the largest distances are highlighted with red on the cloud (a threshold is applied in order to identifythe changes in the two measurements), such as this is visible in Error: Reference source not found.

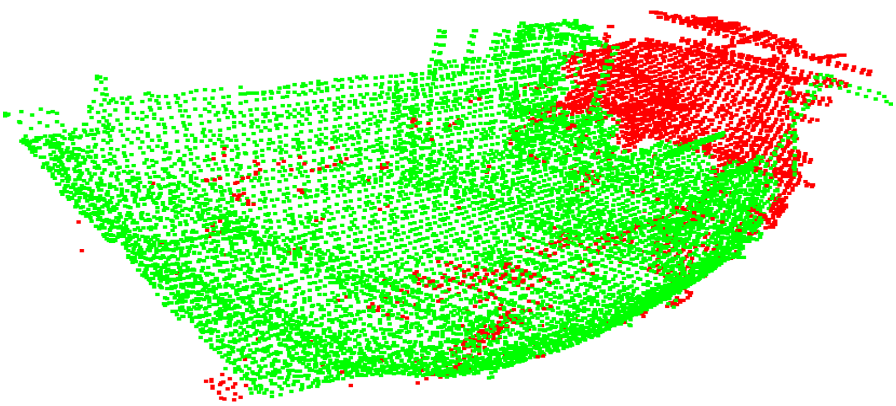


Illustration 11: Laser (i3mainz) 2014 - laser (KSF) 2009 difference

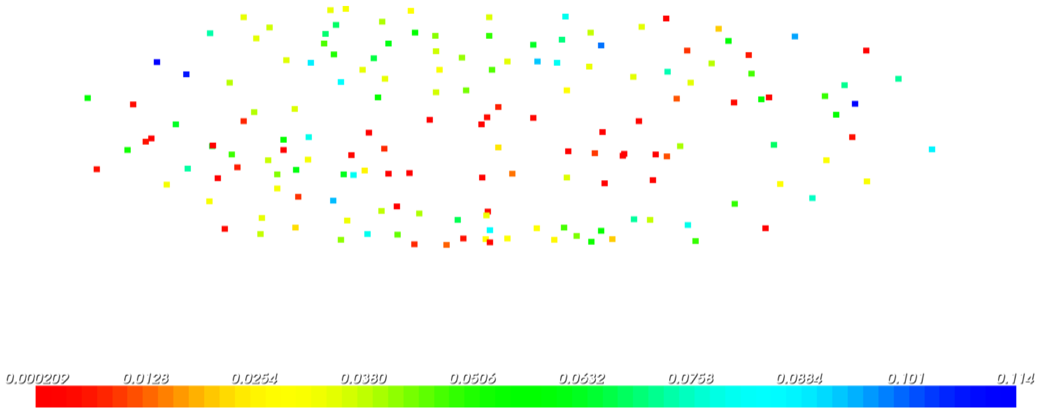


Illustration 12: Dense 3D laser -- sparse Total station data change detection(top view of the ship)

The third Euclidean distance test was performed using dense-dense lidar data from the interior ofthe ship dated from 2009 and 2014 respectively. In this case, the reference (2014) data was approximated with local planes using a least squares approach, and the distances from the nearestneighbour points from the compared (2009) data were considered. The results are shown in Illustration 13.

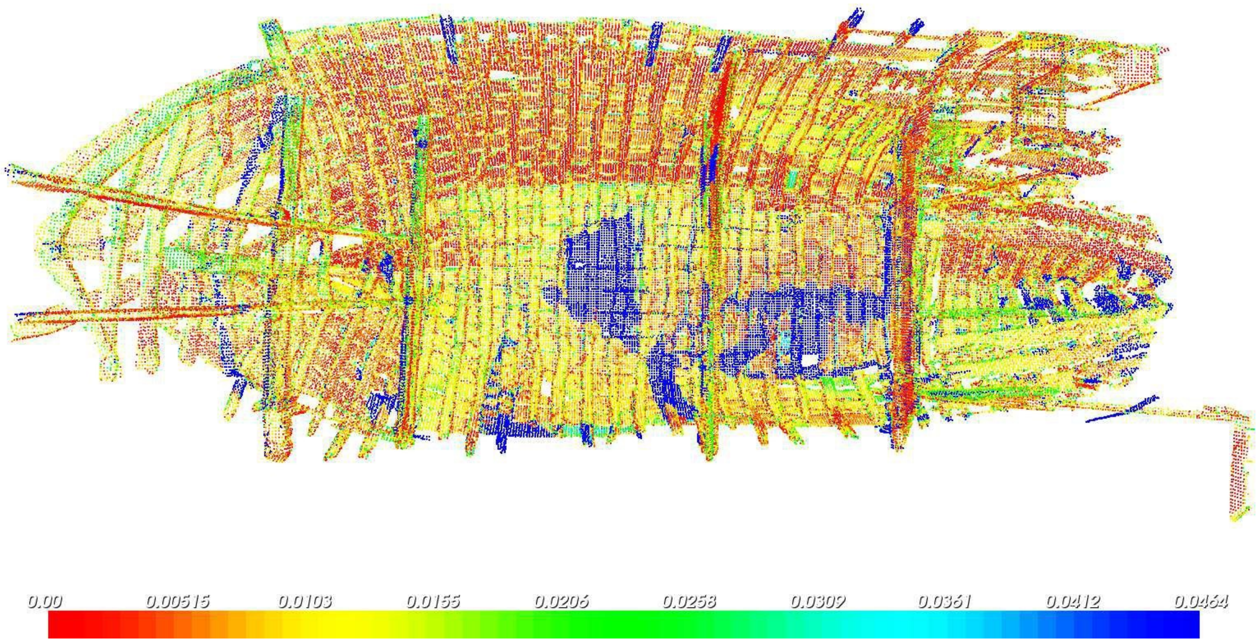


Illustration 13: Interior dense 3D data comparison from 2009 and 2014 (top view of the ship)

The largest differences (dark blue) are due to the missing data from the compared dataset with respect to the reference scan. The medium scale differences (green and its close neighbours on the colour scale) are in 1-2 cm range: this is not too informative, as the measurement absolute noise andthe registration global error summed up is also in 1 cm range. Thus, from this comparison is hard totell which region is affected by deformation in the 1 cm range. Nevertheless, there is a clear message that, large scale (more than 2 cm) deformation are not detected with this method.

Tree structure based difference detection

A more advanced comparison method is based on the octree structure comparison, which is suitable also for detection of trends in the data at a reasonable computational cost. In our case this algorithmwas applied on a down sampled data in order to detect changed in the structure of the ship during the time. Our parameter settings for this change detection were chosen as follows: 5cm voxel grid, 6depth of the octee, and a maximum change detection considered for normalization 30cm. With theseparameter tuning the change detection observed is presented in Illustration 14. In this figure the changes are coded as red—smallest change towards blue—biggest changes. Our finding shows that,the positions close to the metal support pillars are not modified in space, i.e. these were fixed with the support, while the rest of the boat was slightly affected by changes. The dark blue points are the differences between the scans (a part was not scanned in 2009 and which was present in the other scan from 2014.)

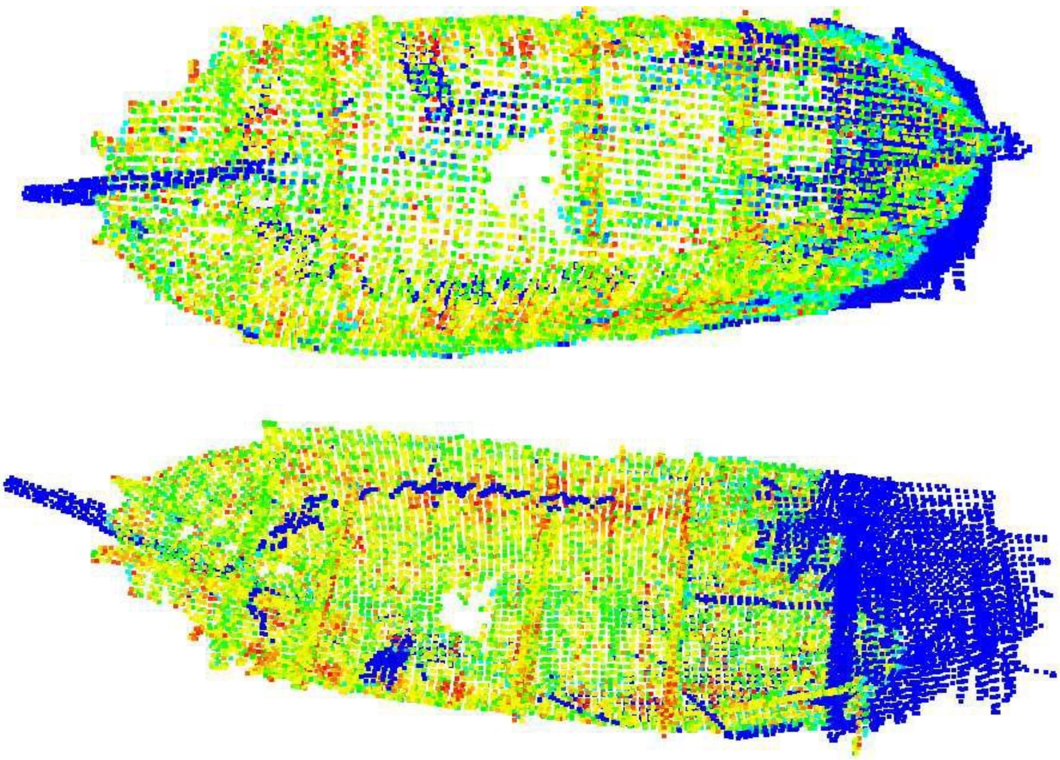


Illustration 14: Change detection with octree structures: bottom(up) and top(down)view of the ship

Cross section analysis

The last analysis was focusing on the 2D cross sections of the different parts of the ship. A summaryof these cross sections are presented below in Illustration 15 and Illustration 16:

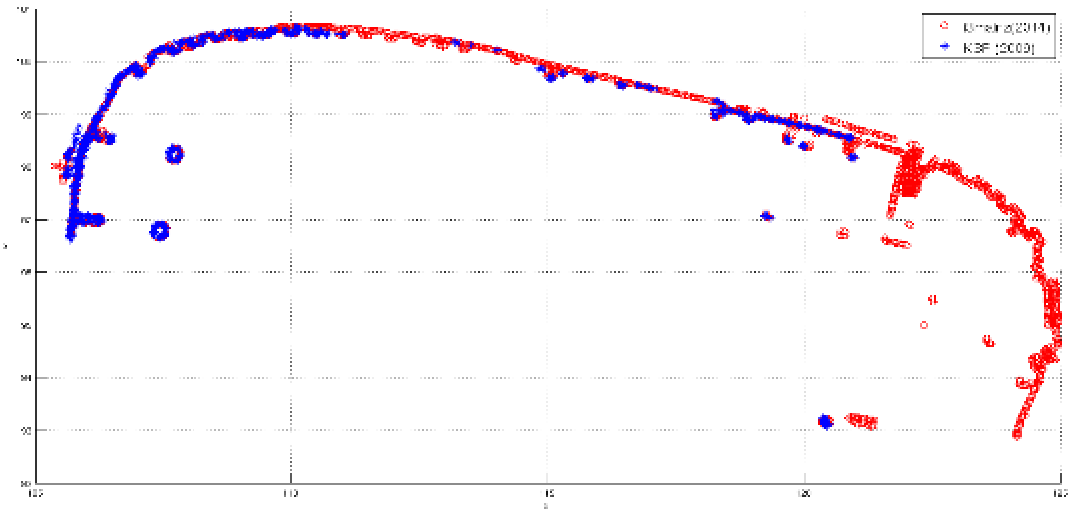


Illustration 15: Cross section cut at 2 (m) height: blue from scan 2009 and red from 20014

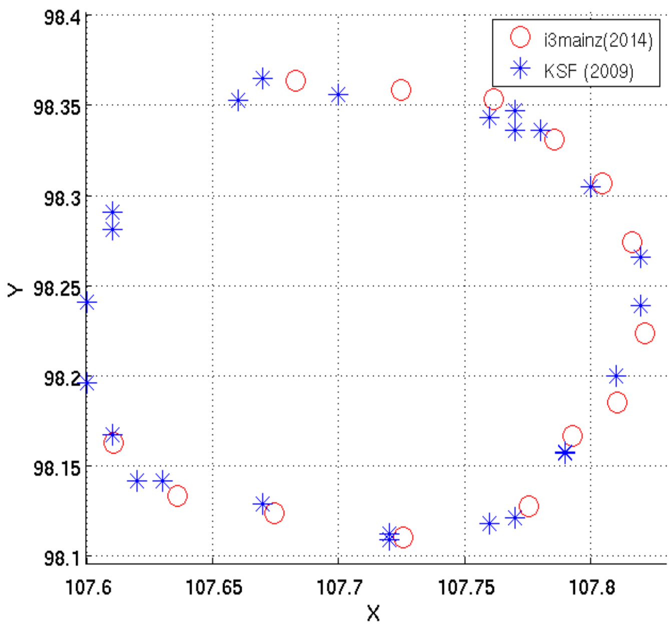


Illustration 16: Zoomed cross section cut blue from scan 2009 and red from 20014

Both illustrations shows the same cross-sections at 2m heights, the later one showing only a timbark. zoomed variant. Large scale deformations are not visible on these figure, however this is not enough to detect small scale changes, as for one scans both interior-exterior measurements are available, while for the second only the internal scans. For a more advanced comparison, the cross correlations should be considered between these two scans in order to detect trends or other changes.

Nevertheless, these methods are also suitable for quick check regarding change detection problem.It is hard to tell, which one would be a gold standard both for the measurement and for the data analysis as, each of these variants have their advantages/disadvantages: depending on the requiredaccuracy and available budget one of these methods could be adopted.

5. Future research perspectives

The research questions addressed in this STSM are still not closed, i.e. the best method to be selected in a large scale object monitoring seems to be a complex issue. However, from technicalpoint of the view the advantages/disadvantages of different approaches can be highlighted based upon the comparison results of this STSM. Even more, this investigation can be easily extended with measured data from future monitoring of the same object.

6. Projected publications of the results

The results of this STSM partially will be presented also at the next MC meeting in Neuchatel. Additionally, the results of this STSM will be presented for the new exhibition of the *Bremen Cog*,which is opening to the public in 2016. Also the publication variant in a journal/conference is considered by the cooperative parts of this STSM.

7. Confirmation by the host of the successful execution of the mission

Attached to this document.

8. Potential interdisciplinary value of research carried out and any other comments

This STSM as well as the case study reflects a true interdisciplinary aspect as long as involves different specialists in the study of this topic. The current STSM would not have been possible torealize without the intensive consultancy of the members from DSM, i3mainz and the main applicant. Also the STSM makes use of the multidisciplinary results from the previous STSM materials as well as the whole output of the case study.

9. Financial summary

The total amount of 710 Eur was completely covering the one week expenses, including the transport on the route Cluj-Bremenhaven-Frankfurt-Cluj as well as the daily expenses (7*45 Eur),the accommodation cost was covered by the DSM

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This research was conducted as part of a three-years-doctoral fellowship funded by the German Maritime Museum (DSM), Leibniz Institute for Maritime History, in Bremerhaven (Germany). The goal set up by the institution was "to investigate the possibilities and limits of non-invasive documentation technologies to study long-term behaviours of large-scale museum objects; in cooperation with the engineering research field and the industry, in order to answer conservation-restauration issues."

Using 3D technologies to look at the deformation(s) on the Bremen Cog, 14th century-wooden vessel on display at the DSM, is an original idea from the author alone. After several years of 'standstill', the question of building an adequate support for the ship came back into the foreground and was discussed during a workshop organised by the museum in November 2013. All experts present agreed that nothing could be proposed without knowing more about the object's current conservation state. The structural weaknesses had to first be identified and understood in order to design the new support. Since wood can be considered as a 'living' entity, the question of deformation was essential, to slow down crack formation and anticipate breakage. Monitoring the geometry would help to understand all types of deformations involved in the process, for example seasonal changes as well as more linear and continuous deformation jeopardizing the structure over the long-term. This is how the journey began.

But it took several months for the idea to take root and become reality. Thanks to the participation of Dr. Ursula Warnke, former DSM director, the author was invited in early 2014 to the COST-Action "Colour and Space in Cultural Heritage" COSCH. This platform became an extraordinary opportunity to gain access to specialists and knowledge in the field of 3D technologies, and to be exposed to new ideas. The role of the COSCH in this project is significant and provided the impulse for the doctoral research. In September 2014, the Bremen Cog became a case study to test on three methodologies for acquiring the ship's deformation(s). Based on the feedbacks from several specialists attesting the scientific relevance of deformation monitoring on an archaeological ship, a doctoral fellowship was funded by the DSM between March 2016 and June 2019.

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