Holl, Kristina; Pallas, Leander; Bellendorf, Paul

Structured Light Scanning as a Monitoring Method to Investigate Dimensional Changes Due to Climatic Changes on Cultural Heritage

Date of secondary publication: 16.12.2025

Version of Record (Published Version), Conferenceobject

Persistent identifier: urn:nbn:de:bvb:473-irb-112221x

Primary publication

Holl, Kristina; Pallas, Leander; Bellendorf, Paul (2025): Structured Light Scanning as a Monitoring Method to Investigate Dimensional Changes Due to Climatic Changes on Cultural Heritage, in: Wolfgang Börner and Hendrik Rohland (Ed.), The World's Heritage in the Digital Age : New Technologies towards sustainable research, conservation and communication, Heidelberg: Propylaeum, pp. 39–49, doi: 10.11588/propylaeum.1449.c20732.

Long Paper

Structured Light Scanning as a Monitoring Method to Investigate Dimensional Changes Due to Climatic Changes on Cultural Heritage

Kristina HOLL, Otto Friedrich University of Bamberg, Germany
Leander PALLAS, Otto Friedrich University of Bamberg, Germany
Paul BELLENDORF, Otto Friedrich University of Bamberg, Germany

Abstract: For a long-term preservation of cultural heritage items, stable climate conditions are necessary. As indoor temperatures will rise in the future due to climate change, chemical reactions take place much more quickly. At the same time, however, relative humidity decreases, which can cause damage, especially in the case of objects consisting of organic composite materials. As reactions to changes in climate depend very much on surrounding circumstances, on past climate patterns, and on the preservation history of an object (conservation treatments, changes in location, etc.), it is generally difficult to forecast future damage to cultural heritage objects that might be caused by climate change. Comparable damage patterns can be found on cultural heritage items which have been subjected to unfavourable climatic conditions over a longer period. This is usually due to excessive use, e.g., numerous events or the incorrect operation of cultural heritage items. This usually leads to inappropriate climatic conditions such as too high temperatures and too high or too low relative humidity combined with high climatic (short-term) fluctuations. Depending on the strain and the exposure time of the prevailing climate, this usually results in the appearance of cracks, loosening and loss of surfaces. With the help of structured light scanning, it is possible to analyse the geometry of historic surfaces in detail and correlate the observed changes with climate measurements. This helps not only to conduct high-resolution monitoring, but also to carry out an individual risk analysis for cultural heritage objects. Two case studies with different composite materials and questions will be used to demonstrate the potential of surface monitoring with structured light scanning: monitoring the effect of climate change on the baroque leather panels in Moritzburg Castle as well as the impact of the conversion of the former Dominican church of St. Christopher in Bamberg on the medieval wall paintings.

Keywords: *Structured Light Scanning—Cultural Heritage—Monitoring—Microclimate—Risk Assessment*

CHNT Reference: Holl, K., Pallas, L. and Bellendorf, P. (2025). 'Structured Light Scanning as a Monitoring Method to Investigate Dimensional Changes Due to Climatic Changes on Cultural Heritage', *Proceedings of the 26th International Conference on Cultural Heritage and New Technologies*, Vienna and online, November 2021. Heidelberg: Propylaeum.
doi: 10.11588/propylaeum.1449.c20732.

Introduction

Climatic fluctuations may have a different impact on artworks depending on their material properties and thickness. Works of art such as wall paintings or leather panels usually consist of different layers of materials (e.g., priming, several color layers, coating), each one reacting differently to changes in climate by swelling and shrinking. The individual behavior of each layer can cause stress inside the composite material, see Bratasz (2013), Erhard and Mecklenburg (1994), Lukomski (2012), Mecklenburg (2010), Michalski (2011). Both short-term and long-term fluctuations of temperature and relative humidity (RH) have an impact on artworks: Short-term fluctuations, which occur on an approximately daily cycle, will affect mainly the surface of an object, especially when there is already damage present. Fluctuations, which occur over a longer period, will also affect the inner layers and the support. Therefore, depending on the frequency and amplitude, climatic changes can cause a variety of damage, such as deformation or cracking of the support or loosening of the surface. Thus, the question of whether climate fluctuations are still safe for the exposed objects can be very complex.

One of the main future effects on cultural heritage items will be the influence of anthropogenic climate change. Increasing weather events, such as heavy rain or long dry periods, pose a threat to the vulnerable historic substance and have an unfavourable effect on the indoor climate. In effect, low humidity levels lead to a high risk of damage to numerous artistic genres, especially to polychrome surfaces such as canvas paintings, leather panels, wallpapers, framed wooden surfaces, and wall paintings. Therefore, irreversible damage, such as cracking, loosening, and loss of substance of the paint etc., can occur. According to the current regional climate data analysis of the “Climate Service Center Germany” (GERICS), there will be up to twelve additional heat days (temperature above 30 °C) in Saxony in the future, see Brasseur, Jakob and Schuck-Zöller (2017). So far, there are only six days per year based on a 30-year average (1971–2000).

The excessive use of a cultural heritage site either due to heavy tourist use (for example in Neuschwanstein Castle) or by the conversion of a historic building which strongly varies from the original purpose is also related to a major risk for damages to the historic fabric and furnishing.

In this paper, two case studies with different situations and questions will be introduced. By using a combination of structured light scanning (SLS) and monitoring the indoor climate, investigations on the behaviour of the different composite materials will be shown. Depending on the result of the in-situ investigation future risks will be discussed and preventive measures will be proposed.

Case studies and methods

The method of examining historic surfaces by a repeated monitoring of reference surfaces with SLS combined with a detailed investigation of the microclimate shall be introduced using the example of the leather panels in Moritzburg Castle as well as the medieval wall painting fragments in the former Dominican church in Bamberg.

Case study 1 – The effect of climate change on the baroque leather panels in Moritzburg Castle

In 2018, 2019 and 2020 the outdoor temperature exceeded 39 °C especially in some parts of eastern Germany. At the same time, long dry periods took place, attributable to global warming. As a result, the temperature inside monuments with valuable historical wall coverings and wall-mounted objects also increased, and the relative humidity sank to critical values below 40% RH. According to the persons responsible on site, this phenomenon has been observed in Germany in this way for the first time.[1] Especially in the region of Saxony, the damaging phenomenon of too low relative humidity inside historic buildings has been observed increasingly after dry summers. Therefore, a detailed analysis of the indoor climate, including the microclimate, is carried out using examples of nationally valuable cultural heritage items. Within the scope of the project "Schadensrisiko für Kulturgut aufgrund zu geringer relativer Luftfeuchte in Innenräumen von national wertvollen Kulturgütern. Analyse und Empfehlungen zum Umgang hinsichtlich der Auswirkungen der globalen, anthropogenen Klimaerwärmung"[2], the baroque leather panels in Moritzburg Castle have been examined among other things.

Fig. 1. Left: Castle Moritzburg from the 18th century is situated in Saxony 15 km north of Dresden. Right: The Chinese Room inside the castle is an example of one of 11 rooms showing original leather panels. The examination of the historic surface was conducted by structured light scanner combined with precise microclimate monitoring (© Kristina Holl).

The hunting lodge of Moritz of Saxony from 1542, which was converted into a baroque palace under August the Strong in the 18th century, displays the world's largest collection of baroque gilt leather panels, see Figure 1. Eleven of the original 60 rooms in the palace still feature embossed, punched, and painted calfskin or goatskin panels, which are being continuously restored, see Schulze (1997) and Schulze (1998). As leather is an organic material that reacts very quickly and strongly to climatic changes, the leather panels in Moritzburg Castle suffer from high temperatures above 24 °C and a decreasing humidity down to under 30% RH. Typical damages are deformations, cracks as well as losses in the original substance. Especially leather panels which have been mounted in the past were fixed with nails and therefore are restrained. As a result, the reaction to fluctuations in temperature and relative humidity propagates especially around seams and mountings. For the examination with the SLS already damaged surfaces were chosen for investigation. Figure 2 shows the result of the SLS of the reference area in the Chinese room combined with an orthogonal colour photography, which was laid below to improve the localisation.

[1] Oral testimony of members of the local institute for diagnostics and conservation of cultural heritage in Saxony and Saxony-Anhalt (IDK e.V.).

[2] Risk of damage to cultural property due to insufficient relative humidity in interiors of nationally valuable cultural property. Analysis and recommendations regarding the effects of anthropogenic global warming), funded by the German Federal Environmental Foundation (Deutsche Bundesstiftung Umwelt, DBU).

Fig. 2. Reference area of the leather panel in the Chinese Room in Moritzburg Castle taken by the SLS and laid on top of an orthogonal colour photograph. The grazing light increases the visibility of cracks and losses along the seed of two leather parts (© Leander Pallas).

Case study 2 – The effect of the use of the former Dominican church of St. Christopher in Bamberg as an auditorium on the medieval wall paintings

The former Dominican church of St. Christopher in Bamberg in Northern Bavaria (Figure 3, left) is a large mendicant church from the 14th and 15th centuries. The church contains a large and complex program of wall painting fragments (Figure 3, centre), which have been uncovered successively during the 20th century, see Hoyer (2009). Extensively renovated between 1999 and 2015, a combined heating system consisting of an underfloor and circulating air heating was installed to use the former church as an auditorium for the University of Bamberg. During an inspection by Pallas (2020), fragments of the wall paintings flaked off and were found on the floor. Especially during the winter months measurements of the indoor climate showed extremely low relative humidity as well as high fluctuations of the relative humidity, see also Figure 4 right.

Fig. 3. Left: A street view of the former Dominican church of St. Christopher in Bamberg. Centre: Wall painting inside the former Dominican church showing a Volto Santo. Right: Reference area of the medieval wall painting taken by the structured light scanner laid on top of an orthogonal colour photography (© Leander Pallas).

Structured light scanning

SLS is a combination of optical triangulation technology (optical distance measurement by angular measurement inside triangles) and interferometry (interaction of waves). The great advantage of this optical method is a fast recording of surfaces at a high resolution, see Eipper et al. (2004).

The measurements have been conducted with a COMET L3D 5M structured light scanner by Steinbichler Optotechnik (now Carl Zeiss Optotechnik) (Figure 1, right). With this method, it is possible to scan areas of varying sizes by changing the lenses. Using a 250 mm lens, an area of 260 x 215 × 140 mm can be examined, and with a 75 mm lens, the area is 74 × 62 × 45 mm. The distance between two measured points also depends on the lens: the smaller the image section, the higher the resolution (250-mm-lens: 100 µm distance, 75-mm-lens: 30 µm). Using the Comet Plus 9.63 software, several scans are combined into a single data file. The scans were carried out in rows with a vertical and horizontal overlap of more than 50% between every single scan. The redundant data reduces the matching errors between the individual scans and guarantees a higher geometrical accuracy for each monitoring area (Figure 2, 3 right), see Drewello et al. (2011).

For the examination of the SLS data, two scans of the same surface are compared using the software GOM Inspect Suite 2020. After a manual orientation, the software relates the scans to each other and calculates a “best-fit orientation” (by specifying an error between 0.05 and 0.1 mm). Afterwards, a comparison of the surfaces can be carried out. For better localisation the comparisons are laid on top of an orthogonal colour photography. In order to demonstrate how much the two scans deviate from each other, the software creates a colour-coded image illustrating the deviation. The scale of the false-colour illustration is selected automatically according to the maximum deviation but can be adjusted manually. In our case, a dark green area means no change; areas that are coloured light green (minimum) to red (maximum) indicate that a convex warping has taken place, while colours from turquoise to dark blue indicate an increasing concave warping (Figure 5, 6, 7), see Drewello et al. (2011) and Holl et al. (2017).

Evaluation of the indoor and microclimate on site

To be able to derive damage risks from the surface comparisons, it is necessary to measure and exploit the microclimate of the investigated area. Therefore, at the beginning of the monitoring on site, measurements of surface temperature, relative humidity, and air temperature have been installed next to the test areas. The data are recorded in a 10-minute interval. Figure 4 shows the temperature and relative humidity distribution for the whole measurement period of the two case studies (left: Moritzburg, Chinese Room, right: former Dominican church, west wall). This helps to get a quick overall view of the distribution of temperature and relative humidity over the course of a certain time. The diagrams show the corridor and the fluctuations in temperature and relative humidity. The statistical analysis gives detailed information about the height of the fluctuations (see Table 1 and 2).

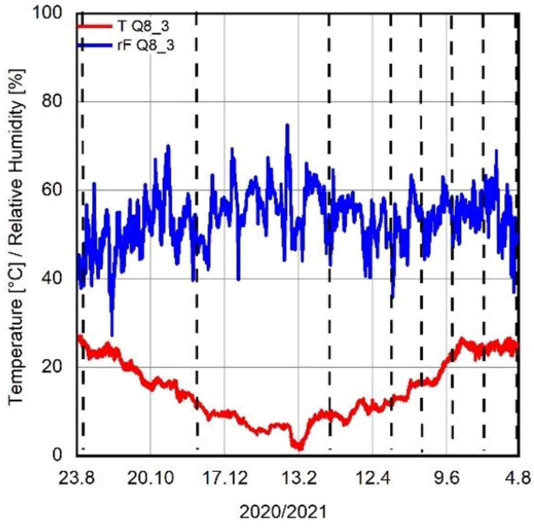
Results and Discussion

Former Dominican church of St. Christopher in Bamberg

Three measurement campaigns were conducted with the SLS (2020-07-06/07; 2020-09-05; 2021-09-22). During each campaign, at least five surfaces were recorded. Figure 5. shows the comparison of scans from September 2020 and September 2021 of the reference area, which is located in the alcove of the west wall. In our case, the paint layers around the edges are prone to movement, in this example ±0.04 mm. Continuous movements in such areas can cause parts to flake off, as can be seen in the lower middle half of the picture. The missing flake can be seen in dark blue, showing a loss of approximately 1.60 mm, whereas the surface right next to it was pushed outwards for about 0.60 mm. The climate data between September 2020 and September 2021 were very similar, see Figure 4 right. However, it should not be neglected that during the heating period, between November and April, the relative humidity does not rise above 40% RH and there are generally strong fluctuations in humidity (minimum: 12.9%; maximum: 72.0% RH; Δ 59.1%; see Table 1). As the wall paintings consist of organic materials which react to the indoor climate the movements and losses in the surfaces can be related to the unfavourable climate.

Leather panels in Moritzburg

In Moritzburg seven measurement campaigns with the SLS were conducted, see dashed lines in Figure 4, left and Table 2. A comparison of the statistical analysis of the climate data between two measurement campaigns helps to interpret the results from the SLS. The greatest change in relative humidity of 43.1% RH (minimum: 27.1; maximum: 70.2% RH) and a change in temperature of 16.2 °C (minimum: 10.9 °C; maximum: 27.1 °C) occurred in the time period from November 25th 2020 till March 9th 2021. Surprisingly the surface reaction only shows a movement of about ±0.15 mm (Figure 6). The highest movement in the leather panel was recorded between May and July 2021. Especially the surfaces which were already damaged show movements of ±0.50 mm to the front (yellow/red areas) or to the back (blue areas) (Figure 7). During that period a change in relative humidity of 19.1% (minimum: 44.3%; maximum: 63.4% RH) was measured. The temperature varied between 15.8 °C and 26.6 °C (Δ 10.8 °C). From a conservational point of view, this climate would not raise concerns. However, due to COVID-19 the museum was closed for some months and reopened in May 2021. Therefore, it is likely that a change in airflow or something similar might have had an effect on the leather panels.



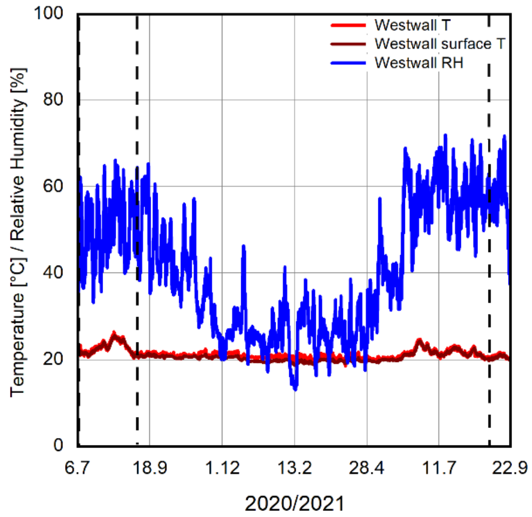


Fig. 4. Left: Line diagram showing the relative humidity (blue) and the temperature (red) next to the reference area in the Chinese room in Moritzburg from August 2020 till August 2021. Right: Line diagram showing the relative humidity (blue) and the temperature (red) in the former Dominican church from July 2020 to September 2021. Dotted lines mark the times of the measurement campaigns (© Kristina Holl).

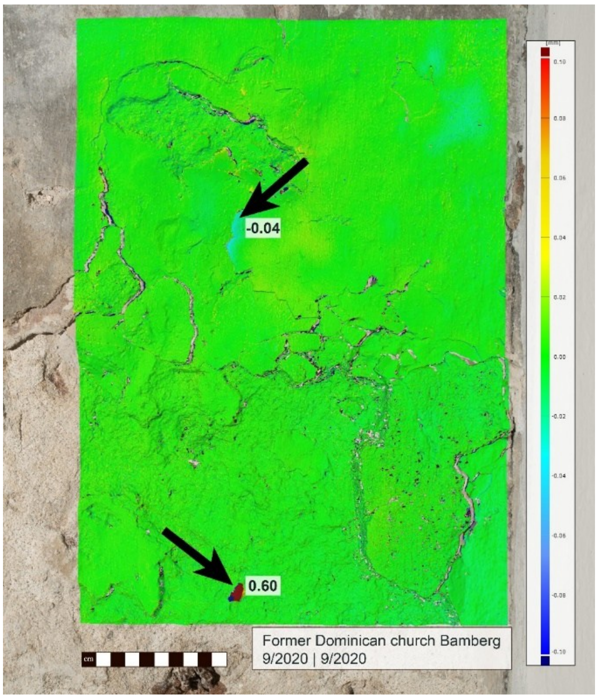


Fig. 5. 3D-Comparison from September 2020 and September 2021 laid on top of a coloured orthogonal photograph of the reference area. Movements along the edges are visible, especially in the lower middle half where a paint layer is flaking off (light blue to dark blue movement to the back, light green to red: movement to the front). The measurements were executed with a 100 µm resolution (© Leander Pallas).

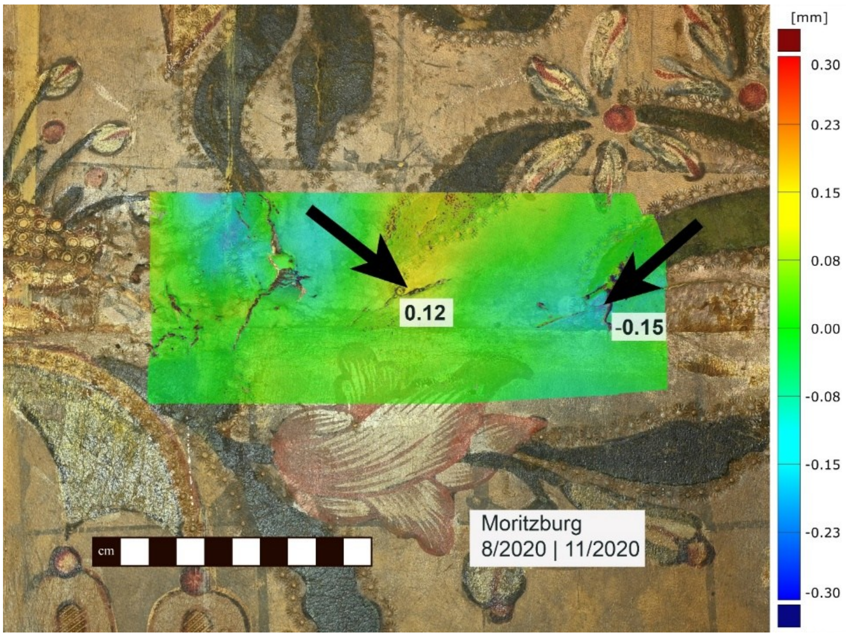


Fig. 6. 3D-Comparison from August and November 2020 laid on top of a coloured orthogonal photograph of the measured area. During the time the highest changes in relative humidity occurred. However, the reaction of the leather panel is low (± 0.15 mm) (© Leander Pallas/ Kristina Holl).

Table 1. Statistical analysis of the indoor climate in the former Dominican church from September 5th 2020 till September 22nd 2021. Measurements were taken next to the reference area in the alcove of the west wall.

	Minimum	**Mean Value**	**Maximum**	**Δ**
Temperature [°C]	18.5	21.0	24.8	6.3.
Surface temperature [°C]	18.6	20.5	24.3	5.7
Relative humidity [%]	12.9	39.9	72.0	59.1

Table 2. Listing of dates of the measurement campaigns in Moritzburg Castle as well as the statistical analysis of the climate data for the time between two measurements. The statistical analysis over the whole period is shown in the last line.

No.	**Date**		**Minimum**	**Mean Value**	**Maximum**	**Δ**
1	August 24th / 25th 2020		n.a.	n.a.	n.a.	n.a.
2	November 25th 2020	Temperature[°C]	10.9	19.1	27.1	16.2
		Relative humidity [%]	27.1	50.3	70.2	**43.1**
3	March 9th 2021	Temperature[°C]	1.4	7.3	11.9	10.5
		Relative humidity [%]	39.7	56.1	74.8	35.1
4	April 6th 2021	Temperature[°C]	6.8	10.3	12.9	6.1
		Relative humidity [%]	40.2	53.1	64.6	24.4
5	Mai 20th 2021	Temperature[°C]	11.4	14.4	17.2	5.8
		Relative humidity [%]	35.8	52.5	63.4	27.6
6	July 2th 2021	Temperature[°C]	15.8	21.7	26.6	10.8
		Relative humidity [%]	44.3	54.7	63.4	19.1
7	August 5th 2021	Temperature[°C]	22.5	24.9	26.6	4.1
		Relative humidity [%]	36.9	54.0	69.0	32.1
Statistical analysis from August 24th 2020– August 5th 2021		Temperature[°C]	1.4	14.8	27.1	25.7
		Relative humidity [%]	27.1	53.5	74.8	47.1

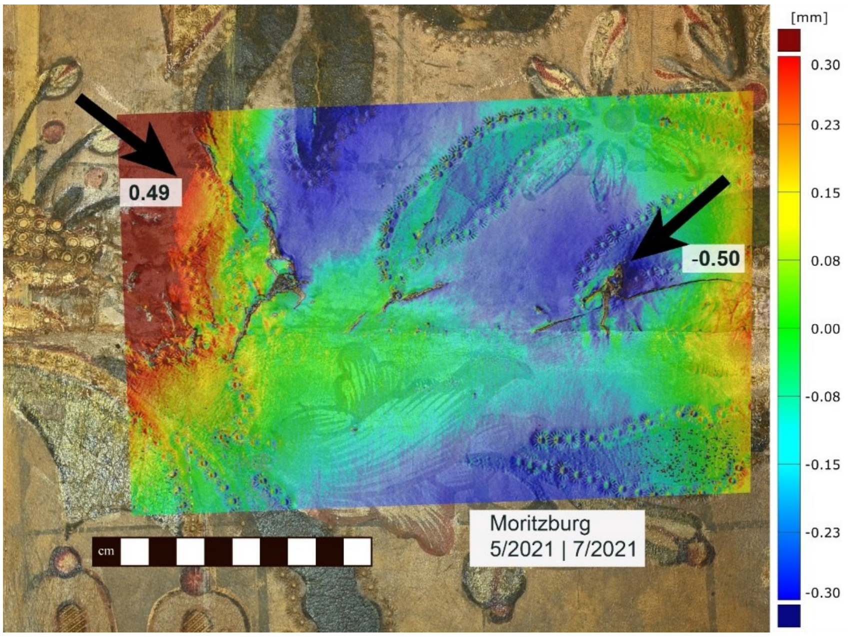


Fig 7. 3D-Comparison from May and July 2021 laid on top of a coloured orthogonal photograph. It shows the strongest movements of all measurement campaigns. A clear shift is visible within the leather panel, especially in already damaged surfaces (light blue to dark blue: movement to the back, light green to red: movement to the front). The measurements were executed with a 30 µm resolution. Here, a movement of about ± 0.5 mm is visible (© Leander Pallas/ Kristina Holl).

Conclusion and Outlook

Using SLS, three-dimensional measurement data of the historical surfaces are available in extremely high resolution. Here, even the smallest movements of the surfaces can be recorded and visualized, comparing measurement campaigns with sub-millimetre accuracy over a long period of time. By using the SLS the investigation of material loss, flaking and development of cracks is possible and movements due to climatic changes on historic surfaces are quantifiable and can be visualised in false colour images. This is always helpful for discussions with stakeholders.

In conclusion, the examined panels show a clear mechanical response to short-term, monthly as well as seasonal changes in the environment. This was especially significant on the leather panels in Moritzburg castle, where changes of ± 0.5 mm were visible at a monthly period.

Concerning the timespan between measurement campaigns one can say that the more sensitive the material is to climate fluctuations, the shorter the measurement interval should be. Using the example of the former Dominican church, the developed monitoring method is very useful for the long-term monitoring of wall paintings. It will be continued at least on a yearly basis.

To find solutions to prevent future damages, the results will be discussed with the owners and stakeholders.

In the former Dominican church, floor heating creates constant high temperatures above 18 °C without any humidification system. This causes very low relative humidity far below 40% RH which would be recommended at least from a conservational point of view. In addition, daily and overall fluctuations are very high (often exceeding 20% RH per day). This is probably due to the ventilation which takes unconditioned air from outside and therefore causes high fluctuations. To improve the situation, one could either lower the heating temperature and/or precondition the air for the ventilation system. This would improve the indoor climate concerning the overall humidity level and reduce short-term fluctuations.

To prevent the historic furnishing in Moritzburg castle from future damage due to high temperatures and low relative humidity the improvement of the shading of the building is one opportunity. Another possibility is the use of intelligent automated ventilating systems. Here windows would open automatically, when the outside conditions are acceptable to keep the indoor climate stable and close when the conditions get inconvenient.

Funding

The results of Moritzburg Castle obtained within the framework of the research project “Schadensrisiko für Kulturgut aufgrund zu geringer relativer Luftfeuchte in Innenräumen von national wertvollen Kulturgütern. Analyse und Empfehlungen zum Umgang hinsichtlich der Auswirkungen der globalen, anthropogenen Klimaerwärmung” (Risk of damage to cultural property due to insufficient relative humidity in interiors of nationally valuable cultural property. Analysis and recommendations with regard to the effects of anthropogenic global warming) were funded by the DBU (German Federal Environmental Foundation, AZ 35598-45) from 2020 to 2021. We thank all project partners, especially the IDK (Institut für Diagnostik und Konservierung an Denkmalen in Sachsen und Sachsen Anhalt e.V.) and the staff from Moritzburg Castle for a fruitful cooperation.

The results of the investigation in the former Dominican Church are taken from Leander Pallas’ Master Thesis.

Conflict of Interests Disclosure

The authors assure, that there is no conflict of interest in this paper.

Author Contributions

Conceptualization: Holl, Pallas, Bellendorf
Data curation: Holl, Pallas, Karl
Formal Analysis: Holl, Pallas
Funding acquisition: Bellendorf, Holl
Investigation: Holl, Pallas, Karl
Methodology: Holl, Pallas
Project Administration: Holl, Pallas
Resources: Holl, Bellendorf
Software: contributor names
Supervision: Holl, Bellendorf
Validation: Holl, Pallas, Bellendorf
Visualization: Pallas, Holl
Writing – original draft: Holl, Pallas
Writing – review & editing: Schmölder, Bellendorf

References

Bratasz, L. (2013). 'Allowable microclimatic variations for painted wood', *Studies in Conservation* (58), pp. 65–79.

Erhardt, D. and Mecklenburg, M. (1994). Relative-humidity re-examined, *Preventive Conservation. Practice, theory and research. International Institute for Conservation of Historic and Artistic Works Ottawa,* 12–16, September 1994. London. pp. 32–38.

Lukomski, M. (2012). 'Painted wood. What makes the painting crack?', *Journal of Cultural Heritage*, Vol. 13, pp. 90–93.

Mecklenburg, M. (2010). *Determining the acceptable ranges of relative humidity and temperature in museums and galleries. Part 1 Structural response to relative humidity* available at https://repository.si.edu/handle/10088/7056 (Accessed: 25 January 2022).

Michalski, S. (2011). *Agent of deterioration: Incorrect relative humidity*. Available at: https://www.canada.ca/en/conservation-institute/services/agents-deterioration/humidity.html#det3 (Accessed: 25 January 2022).

Brasseur, G.P., Jakob, D. and Schuck-Zöller, S. (eds.) (2017). *Klimawandel in Deutschland, Entwicklung, Folgen, Risiken und Perspektiven*, New York.

Schulze, A. (1997). 'Die Ledertapeten im Schloß Moritzburg', in Magirius, H. and Dülberg, A. (eds.) *Denkmalpflege in Sachsen 1894–1994.* Teil I, Weimar, pp. 229–240.

Schulze, A. (1998). 'The application of the "low pressure" technology in the conservation of gilt leather wall hangings in situ – a report about our experiences', *The Conservation of Gilt Leather / La Conservation du cuir doré,* Postprints of the 5th Interim Meeting in Brussels (25.–27.03.1998). ICOM-CC, pp. 32–35.

Pallas, L. (2020). *Monitoring as a maintenance concept in cultural heritage buildings using the example of the former Dominican church in Bamberg*, Master Thesis unpublished.

Hoyer, S. (2009). *Die Wandmalereien der Dominikaner in Bamberg. Kunsttechnologische Analyse des Malereibestandes und beispielhafte Vermittlung komplexer Zeitschichten*. PhD. University of Bamberg.

Eipper, P.B., Frankowski, G., Opielka, H. and Wenzel, J. (2004). *Ölfarben-Oberflächenreinigung. Die Reinigung der Ölfarbenoberflächen und ihre Überprüfung durch das Raster-Elektronen-Mikroskop, das Niederdruck-Raster-Elektronen-Mikroskop, die Laser-Profilometrie und die 3D-Messung im Streifenprojektionsverfahren,* Munich.

Drewello, R., Wetter, N., Rahrig, M. and Bellendorf, P. (2011). '3D-Dokumentation mittelalterlicher Glasmalerei mit der Methode der 3D-Weißlicht-Streifenprojektion' *Konservierung mittelalterlicher Glasmalerei im Kontext spezieller materieller und umweltbedingter Gegebenheiten*, Stuttgart, pp. 142–154.

Holl, K., Rahrig, M. and Janis, K. (2017). Multi-view-monitoring of dimensional changes of wooden panels due to changes in the microclimate at Linderhof Palace, *Preventive conservation in historic houses and palace-museums: Assessment methodologies and applications,* Palace of Versailles November 29th–December 1st 2017. pp. 272– 283, Available at: https://www.larcroa.fr/wp-content/uploads/ROCHE_VERSAILLES_2017-vers-anglaise.pdf (Accessed: 25 January 2022).