Fraunhofer

Fraunhofer Technologies

for Heritage Protection in Times of Climate Change and Digitization

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TABLE OF CONTENTS

TABLE OF CONTENTS

INTRODUCTION

FOREWORD

Prof. Dr.-Ing. habil. Reimund Neugebauer, President of the Fraunhofer-Gesellschaft

Prof. Dr.-Ing. habil. Reimund Neugebauer, President of the Fraunhofer-Gesellschaft © Bernhard Huber

The development of technical solutions and innovations is a central task of science and research. The Fraunhofer-Gesellschaft is responding to current societal challenges such as climate change, scarcity of resources and the digital transformation with strategic initiatives to develop system-relevant solutions on an interdisciplinary and collaborative basis. This also includes the preservation of cultural heritage, which is directly or indirectly threatened by the effects of climate change such as heat waves, droughts or rising sea levels. The aim of the measures is to strengthen the resilience of cultural heritage and preserve it for future generations.

In the field of cultural heritage, we are strengthening both the networking of the institutes within the Fraunhofer-Gesellschaft and with national and international partners from science and industry. For this reason, the Fraunhofer Executive Board has been supporting the FALKE project, in which scientists, together with museums and cultural institutions, have further developed innovative Fraunhofer technologies for the protection of cultural heritage. Examples include the development of ORMOCER®s for the restoration of the gold enamel paintings in the Green Vault in Dresden, ultrasound tomography for the examination of valuable sculptures at the Staatliche Kunstsammlungen Dresden, and an ontological database for cultural heritage protection. The need is also reflected in the numerous continuing third-party funded projects, such as the German BMBF project KERES for research into the future effects of extreme climate events on cultural assets or the EIT KIC Culture & Creativity, the largest EU project in the cultural sector to date. These are based, among other things, on preliminary work carried out by FALKE I and II, such as the ontological data platform or the Fraunhofer technology Cultlab3, an automated scanning line that enables entire museum collections to be digitized in 3D.

Fraunhofer is one of the pioneers in researching the effects of climate change on cultural heritage and developing novel digitization technologies. We want to further strengthen this role, especially through our leadership in the new EIT KIC Culture & Creativity, in order to preserve the irreplaceable cultural heritage with sustainable future strategies, innovative technologies and interconnected competencies.

INTRODUCTION

Dr. Johanna Leissner, coordinator (Fraunhofer EU Office Brussels), and Sabrina Rota (Fraunhofer ISC)

The European Union gives cultural heritage a high political priority: "The Union preserves the richness of its cultural and linguistic diversity and ensures the protection and the development of Europe's cultural heritage." (Article 3.3 of the Lisbon Treaty of 2009).

Cultural heritage in its entirety, be it materially in the form of cultural and industrial landscapes, buildings, monuments, books, manuscripts or art objects, be it immaterial as knowledge, skills, customs, oral traditions and performing arts, is an important source of our identity. It serves as inspiration for innovation and creativity for each and every one of us as well as for the society. It also represents the topic of sustainability – not to consume resources, but to preserve them for future generations because cultural heritage is a non-renewable resource. Unfortunately, in the recent past, the uncertainties paired by acts of war with the consequences of climate change and the years of pandemic, makes us feel that we are entering a new era. Anywhere in the world the limitations and loss of our natural and cultural resources can be experienced in an unprecedented scale and speed.

Politics, industry and society is looking for sustainable solutions. **Science and research have demonstrated their potential to act as indispensable drivers for our societies in offering solutions to cope with the grand challenges.**

Recently, the EU OMC expert group "Strengthening cultural heritage resilience for climate change" examined thoroughly the **role of research and innovation**. It was found that research is **paramount and fundamental in understanding the threats posed to our cultural heritage and to develop adaptation and mitigation measures for preserving and protecting cultural heritage**.

In Germany and Europe, the Fraunhofer-Gesellschaft as the leading institution for applied research in particular has a special role to play with its innovative, technological research in contributing to the preservation of our cultural heritage and to sustainable development.
Since 1986, Fraunhofer Institutes have participated in German, European and international research projects. Only to name a few successful examples of Fraunhofer innovations introduced in the market:

- organic-inorganic protective coatings (ORMOCER®s) for mediaeval stained-glass windows,
- hygrothermal whole building simulation tool (WUFI®) to simulate indoor climate conditions and energy demand,
- glass sensors for monitoring the environmental conditions of outdoor and indoor cultural assets,
- 3D automated digitization scanning of art objects (CULTLab 3D) – Europa Nostra Award 2018.

Dr. Johanna Leissner,
coordinator

In 2008, Fraunhofer has founded, together with the Prussian Foundation for Cultural Property (SPK) and the Leibniz Association with its 8 research museums, the German Research Alliance Cultural Heritage; in 2014 the Alliance was extended by the State Collections Dresden (SKD) and the Saxon State and University Library (SLUB). More than 22 institutes of the Fraunhofer-Gesellschaft have since then pooled their expertise in this field and work closely together. They cooperate not only with the research alliance partners but also with many other external partners amongst them the University of Oxford, the Saar State Monuments Office, Potsdam University of Applied Sciences, Treasury of the Residenz Munich, University of Freiburg. The basis for the success of the Fraunhofer Institutes together with their partners in the field of cultural heritage is the targeted funding by the Executive Board of the Fraunhofer-Gesellschaft.

Following projects have been supported by the Executive Board with roughly 5 mio € in the past 10 years

- application of plasma treatments for cultural heritage,
- FALKE I – protecting our cultural heritage with Fraunhofer innovations,
- Pompeii sustainable preservation project,
- virtual heritage expo of Fraunhofer technologies,
- FALKE II – cultural heritage in danger – effects of climate change and opportunities of digitalization.

The various projects focused on innovative green conservation materials, new methodologies and analysis methods, socio-economic studies, new digitalization technologies and artificial intelligence incorporated into a tailormade ontological data platform. The broad scope of expertise and tools developed by Fraunhofer Institutes will be presented in this book.

As the preservation of our cultural heritage is a task for society as a whole Fraunhofer-Gesellschaft is taking its responsibility serious and has thus been continuously investing in heritage research. Without this internal funding for the so-called FALKE I and FALKE II projects Fraunhofer Institutes would not have been able to join their forces and contribute significantly to make the German Research Alliance an active and innovative network in Germany and Europe to provide innovative solutions to safeguard cultural heritage for future generations.

CHAPTER 1

THE FALKE KNOWLEDGE BASE

THE FALKE KNOWLEDGE BASE

Jürgen Moßgraber, Tobias Hellmund, Jürgen Reuter (Fraunhofer IOSB)

1. CONCEPT OF THE KNOWLEDGE BASE

To support the knowledge management in cultural heritage protection, Fraunhofer IOSB developed a Knowledge Base, which is an ICT platform able to collect and integrate multisource information in order to effectively provide complete and updated situational awareness and decision support for innovative measurements improving cultural heritage resilience, including new solutions for maintenance and conservation. It is meant as decision support platform for cultural heritage stakeholders and is easily configurable and extendable.
To improve the situation awareness of decision makers the system supports several levels of data integration, aggregation and linking:

- integration of expert knowledge,
- connection of sensors for comprehensive monitoring and reporting,
- data analysis of complex processes with an open interface for easy integration of new algorithms,
- semantic and geographic linking of analysis data and multiple domain information.

The backbone of this information network is an ontology, which connects the data of the different domains, like cultural heritage, climate change, crisis management, regulations, sensor data management, buildings, materials and many more.

Through this method, integrated data can be retrieved and visualized in many ways. Versatile mapping technologies can be integrated, allowing the combination of different geospatial referenced data sets. Figure 1 shows an example, where the depth of the sea (green-blue layer) from satellite data, underwater sonar mapping (red-brown layer) and sensor data (blue markers and popup) are combined and placed on a background map. Furthermore, data from a local weather station is displayed.

The following sections start with examples from real world applications of the knowledge base, followed by two new tools of the platform, the Action Finder and the Evacuation Planner. Finally, the ontology is presented.

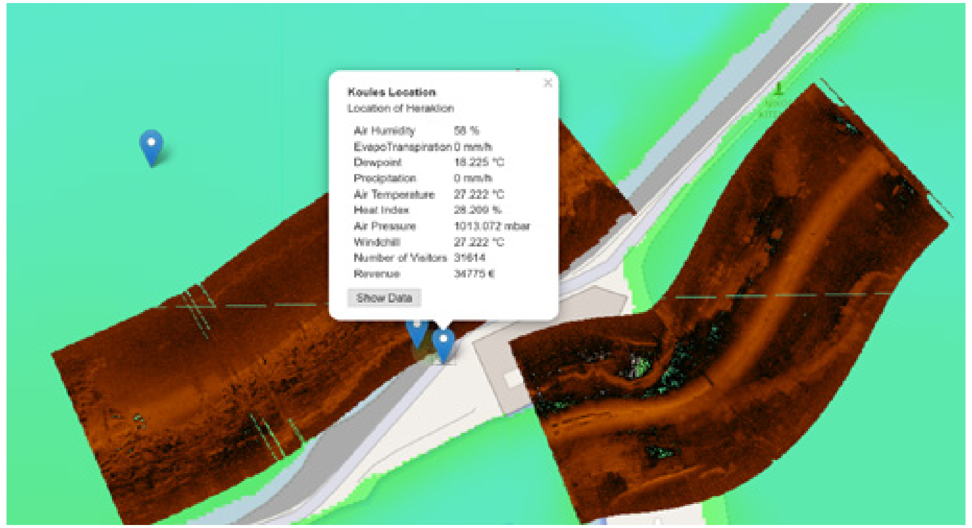


Figure 1:
Visualizing geospatial data from different sources
© Map: OpenStreetMap

2.1 Example from the FALKE project

In the context of the FALKE project, the Knowledge Base makes the broad portfolio of knowledge and services of the members of the Research Alliance Cultural Heritage accessible (“the FALKE Knowledge Base”). Members of the alliance can add their areas of expertise as well as example projects and data. Figure 2 shows the entry page of the FALKE Knowledge Base. The top buttons offer quick access to the researched use cases, analysis services, research results and members of the consortium. Two components show further information: the map-component on the left shows the location of Fraunhofer Institutes in the database and the table gives a browsable view with quick links within the Knowledge Base and the respective websites of the institutes.

2.2 Example from the KERES project

The Knowledge Base has been implemented in several use cases; one of these is within the project KERES (Protecting Cultural Heritage from Extreme Climate Events – funded by the German Federal Ministry of Education and Research). KERES researches the effects of climate change and severe weather events on built cultural heritage and parks. The focus is both on preparedness, as well as on the adaption to climate change. The following implementation in Figure 3 shows a map with the Cologne Cathedral highlighted. As information in the underlying ontology is interconnected and can simply be extended, the case study is complemented with information provided by the Climate Service Center Germany (GERICS), in which an outlook about the coming climatic conditions of the case study is presented. Cultural heritage managers can learn from it about the expected climatic conditions in the region and the potential threats for their heritage site.

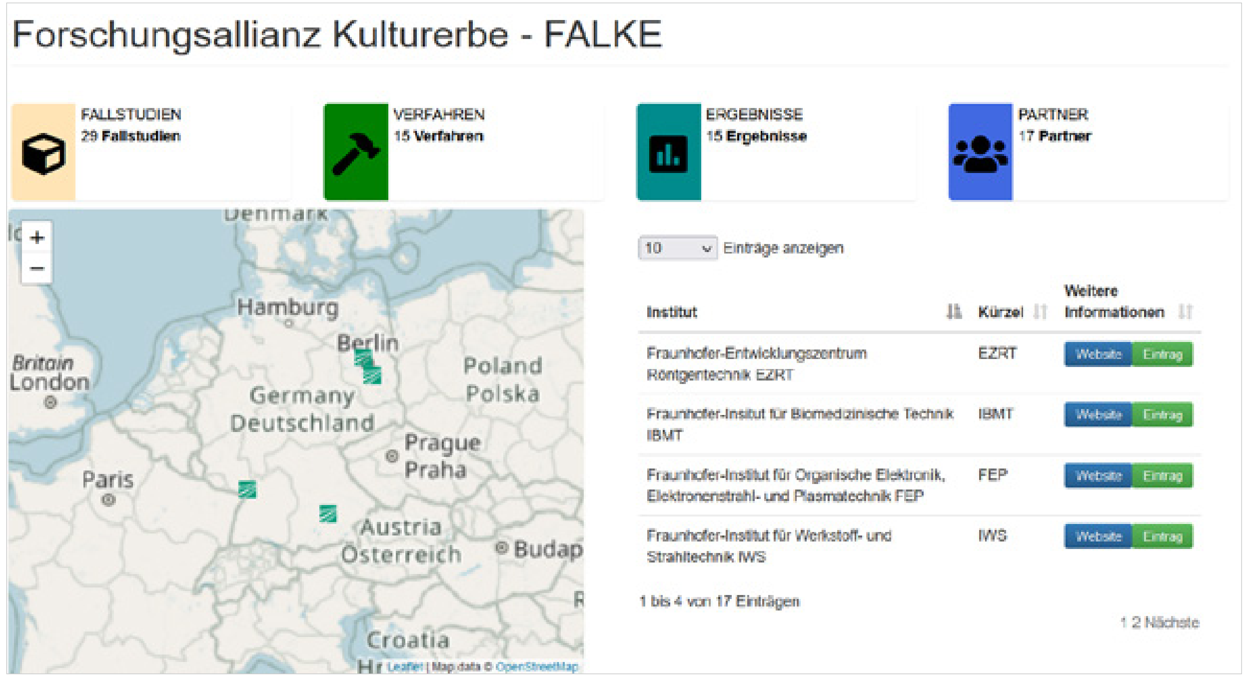


Figure 2:
The entry page
of the FALKE
Knowledge Base
© Fraunhofer IOSB

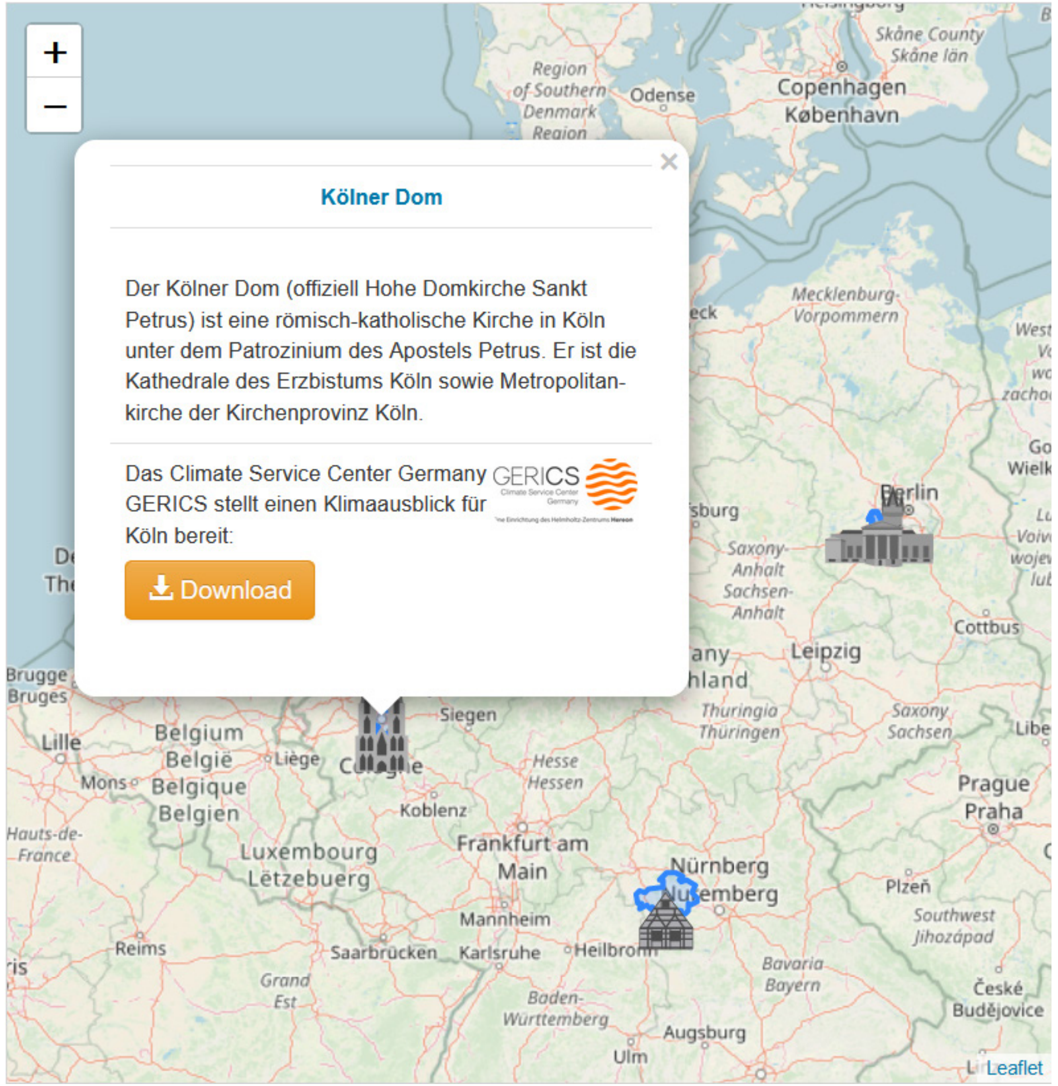


Figure 3: Combination of external with internal data in the KERES Knowledge Base © Map: OpenStreetMap

3. ACTION FINDER

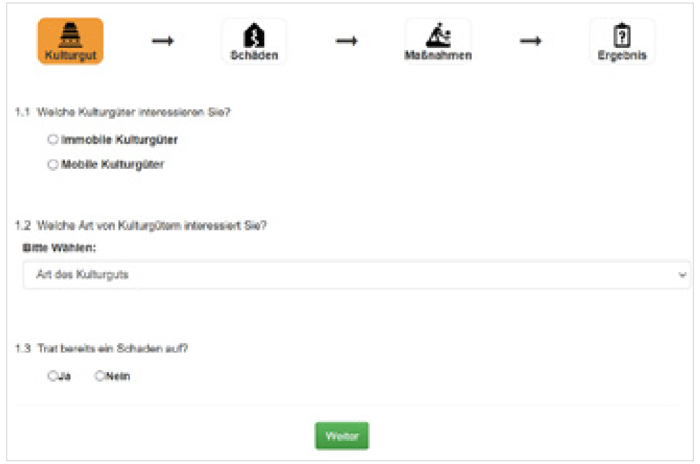


Figure 4: The Action Finder wizard © Fraunhofer IOSB

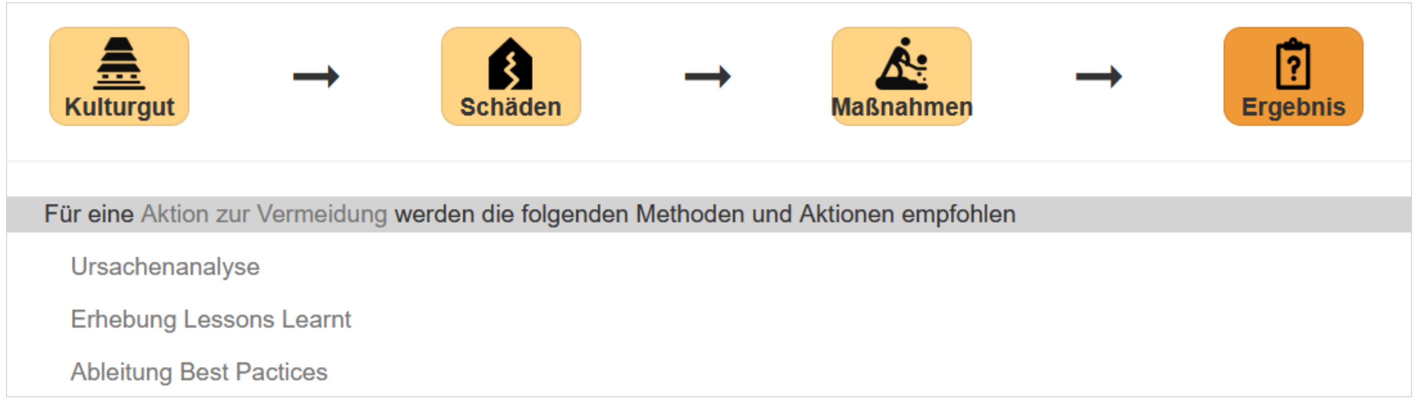
After having learned about the possible threats to a cultural heritage site, a cultural heritage manager might want to learn about actions against the imposed threats: the previously collected information can be used in the Action Finder, another component of the developed Knowledge Base.

In several workshops, the interdependences of effects, such as rain, heat, hot-and-cold cycles, their outcomes and measures to effectively provide shelter against these threats have been discussed to provide another tool, by which cultural heritage managers can learn about suggested actions against specific threats. The Action Finder is designed as wizard and works with sequenced questions (see Figure 4). Based on the answers to these questions, it guides the user through the information in the Knowledge Base and offers specific suggestions to protect cultural heritage.

The questions first help to categorize the cultural heritage at hand. Secondly, it is determined what kind of damages might occur. Thirdly, the type of requested action has to be specified: actions are distinguished based on the urgency. Lastly, specific actions are retrieved from the Knowledge Base, which the user can review and decide, what measures can appropriately be implemented.

The results for the query are displayed in a list and shown for each kind of desired action (see Figure 5). Quick links lead the user to the corresponding entries in the Knowledge Base to allow further research.

Figure 5: Excerpt from the list of results with actionable measures © Fraunhofer IOSB



4. EVACUATION PLANNING

Europe has a significant cultural diversity together with exceptional ancient architectures and artwork collections that attract millions of tourists every year. There are almost 400 UNESCO sites in Europe, located in different Climatic European Regions. These invaluable assets have to be preserved for future generations. Catastrophic events, such as the Fire of Notre Dame in 2019 impose a substantial threat to these assets. Environmental factors, worsened by the increasing climate change impact, or anthropogenic influences impose significant threats to cultural heritage assets as monuments, historic structures, settlements and archaeological sites.

Previous research found a lack of preparedness of museums and cultural heritage administrations against catastrophic events. In several workshops, held in the context of the FALKE project, we were able to acknowledge the lack of preparedness; even further it was found that first responders, such as firefighters, are usually not familiar with the specific needs of cultural heritage assets during a deployment. An example would be the need to extinguish fires in a water saving way or specific transportation requirements during an evacuation.

The main reason for this information gap is the lack of coordination between cultural heritage managers and fire fighters in the forefront of an emergency.

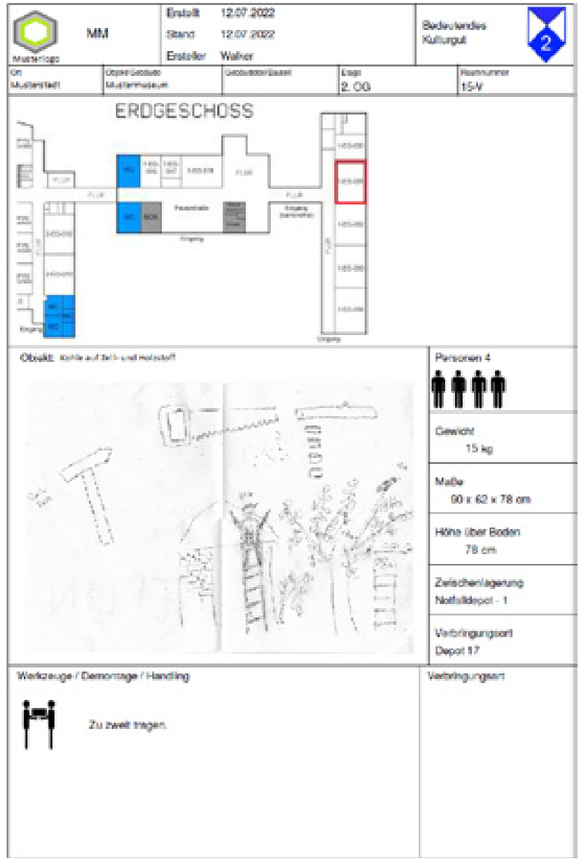


Figure 6: Exemplary route card with hypothetical data © Hellmund

To overcome this gap, cultural heritage managers and fire fighters need to cooperate and exchange information. As fire fighters are used to route cards, these form an appropriate way to provide information to the fire fighters in case of an emergency: route cards usually contain information about how to reach specific spots within a building. By transferring route cards to cultural heritage assets with descriptions about handling and specific requirements, fire fighters can appropriately manage cultural heritage assets during a fire.

To offer a low-threshold possibility for the creation of route cards, Fraunhofer IOSB has developed the software WALKER. WALKER allows the creation and management of route cards for museums. The development, especially the format of the route cards, has been accompanied by professional fire fighters and colleagues from cultural heritage management, to ensure an applicable solution.

Figure 6 shows an exemplary route card. In the top row, it shows a logo of the corresponding museum, the date of creating the route card and a prioritization of the cultural heritage asset. The second row shows information about the location of the asset, such as place, building and room number. The third row provides space for a map, in which the asset is located. The fourth row is utilized to show a picture of the asset itself. Furthermore, information on how many persons are required to evacuate the asset and the extends and weight of the asset are given. Lastly, information on handling and storage are given. It is possible to append information and pictures, if necessary.

The application offers a web-based view and can be accessed with any modern web browser. Users can manipulate images and data through dedicated forms and save, update or delete route cards, as shown in Figure 7. A tabular view offers all created route cards and allows cultural heritage managers to keep track about which assets are prepared.

As route cards contain sensitive information, it is not intended to be used as public online service: the application can be installed as on-premise service within the infrastructure of a museum. WALKER allows the management of assets of several separated museums, but it does not require it.

Figure 7:
Creating, editing and updating route cards © Moßgraber

5. THE KERES ONTOLOGY

Just like all virtually more complex software systems, FALKE uses a database for storage, management and retrieval of data. However, rather than building upon a standard relational SQL database, FALKE deploys a graph database with support for semantic reasoning based on the web ontology language OWL, also called knowledge base in contrast to an ordinary relational database. While relational databases are best for large sets of data records organized in tables, a knowledge base comes into play when data records are heavily linked, as, for example, in ordered lists, tree structures or general graph-like structures. Tree structures are also used to create a hierarchy of classes for categorization of object entities and defining properties to establish links between object entities. Typically, a knowledge base also supports reasoning to some degree, based on the features on the ontology that is used for the underlying modelling. An ontology consists of terminological components, also called TBox, somewhat corresponding to modelling an SQL database with tables and fields, but with additional features for supporting graph-like structures and reasoning. The assertion components of an ontology, also called ABox, contain the actual knowledge facts, somewhat corresponding to the data records stored in SQL database tables.

FALKE makes heavy use of graph-like structures, as we will see. All of these structures are modelled and managed with the help of an ontology.

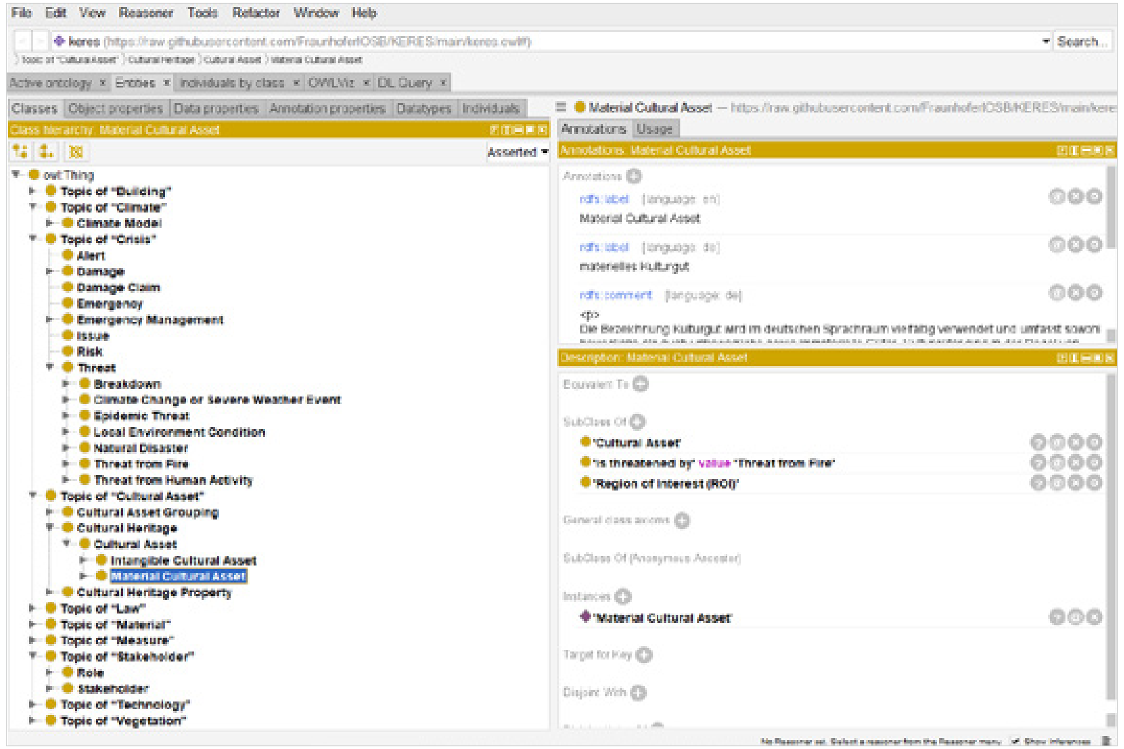


Figure 8:
The Ontology used in FALKE as shown with the Protégé Ontology Editor
© Fraunhofer IOSB

5.1 Cultural heritage, climate change, crisis management

The ontology used in FALKE evolved from the earlier HERACLES project (HEritage Resilience Against CLimate Events on Site – funded by the European Union's Horizon 2020 research and innovation programme) as well as from the on-going KERES project.
In HERACLES, an ontology was created with terminological support for cultural heritage buildings under the risks of climate change. For example, the HERACLES ontology defines some basic classes like Cultural Heritage, Asset, Role and Stakeholder for the classification of artefacts and owners or asset managers and alike, but also classes like Damage, Effect and Action for supporting the process of recording the physical state of cultural heritage, and analysis and response to threats and damages.

In the KERES project, building on the HERACLES ontology and a mind map created from interviews with numerous stakeholders in the area of cultural heritage protection, the ontology was consolidated and extended. The HERACLES hierarchy of classes not only was refined with new classes, but all classes have been structured as a set of topics, and completely new topics have been introduced, such as the topic of climate. Also, while the HERACLES ontology was in English only, in KERES, all of the terminology is now available in both, English and German language. Moreover, for many relevant terminological as well as assertion components, a detailed description has been added. All of these extensions and enhancements from the KERES ontology are now also available in FALKE. Furthermore, in FALKE the ontology was further extended to cover cultural heritage terms items as well as available analysis methods and technologies.

We give examples of some of the more recent concepts in our ontology.

5.2 Regions and Points of Interest (ROIs and POIs)

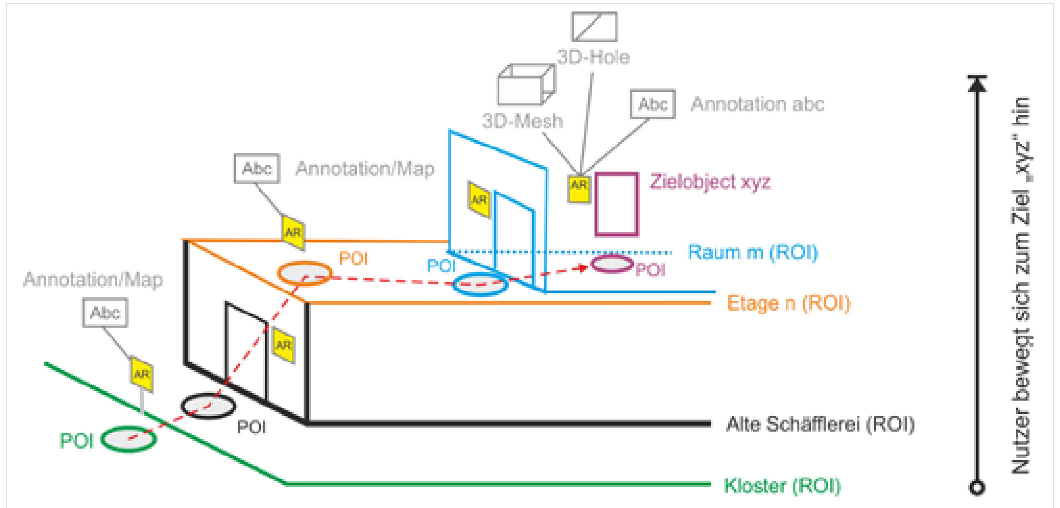
Maybe the most prominent example for a graph-like structure in FALKE is the use of so-called ROIs and POIs.
A region of interest (ROI) defines the boundaries of a volume or area. Typically, ROIs are defined hierarchically. For example, an ROI may specify the boundaries of a specific building. The building may contain several storeys, each represented by another ROI. Boundaries and orientation of children ROIs are specified relative to their parent ROI's origin coordinate system. Taking up our example, each storey itself may contain several rooms, again each room represented by another ROI. And even each room may be further subdivided into another set of ROIs, for example the showcases in a museum. In summary, ROIs typically build a hierarchy, that is a tree-like structure, with, in our example, the building as the root node of the tree, and the showcases as leaf nodes.

Another example for the use of ROIs is the hierarchy of administrative units when modelling data related to geographical locations, e.g. when displaying locations on a map (see Figure 10). For example, in Germany, the country can be subdivided into federal states; area states can be further subdivided into districts, and rural districts into municipalities.

A point of interest (POI) defines the location of something that is of interest, for example the place where some artefact is located, or, in the context of a virtual reality, the place where some virtual object should be displayed within a room. A POI is typically located within a ROI, specifying its location by specifying coordinates relative to the containing ROI's origin. In contrast to ROIs, POIs do not have a parent POI or children POIs – in the end, they are simple points without spatial extent. However, any sequence of POIs may be linked to form a path, possibly even across several ROIs that contain all involved POIs.

While modelling sequences of POIs and trees of ROIs is possible even in relational SQL databases using foreign keys for linking, the table-based approach of storing data records just does not match the graph-like structures well. In contrast, graph databases and, in particular, ontologies just perfectly match the needs of storing, managing and retrieving graph-like data structures.

Figure 9: ROIs and POIs © Fraunhofer IOSB



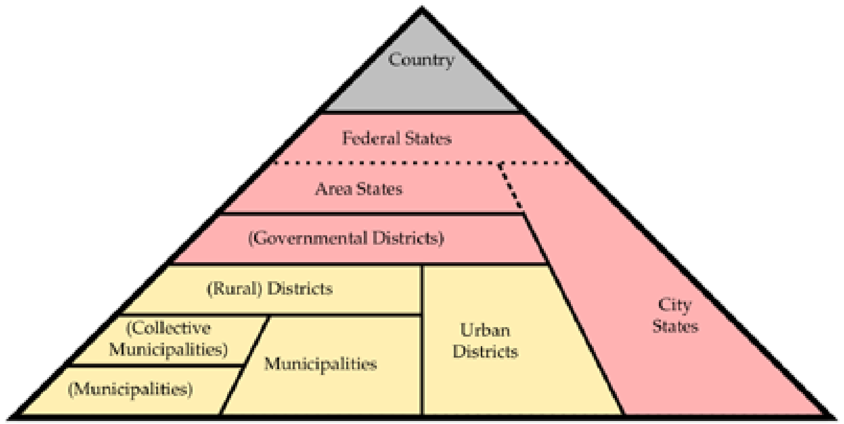


Figure 10: ROIs: Administrative Units in Germany © Fraunhofer IOSB

5.3 Route cards

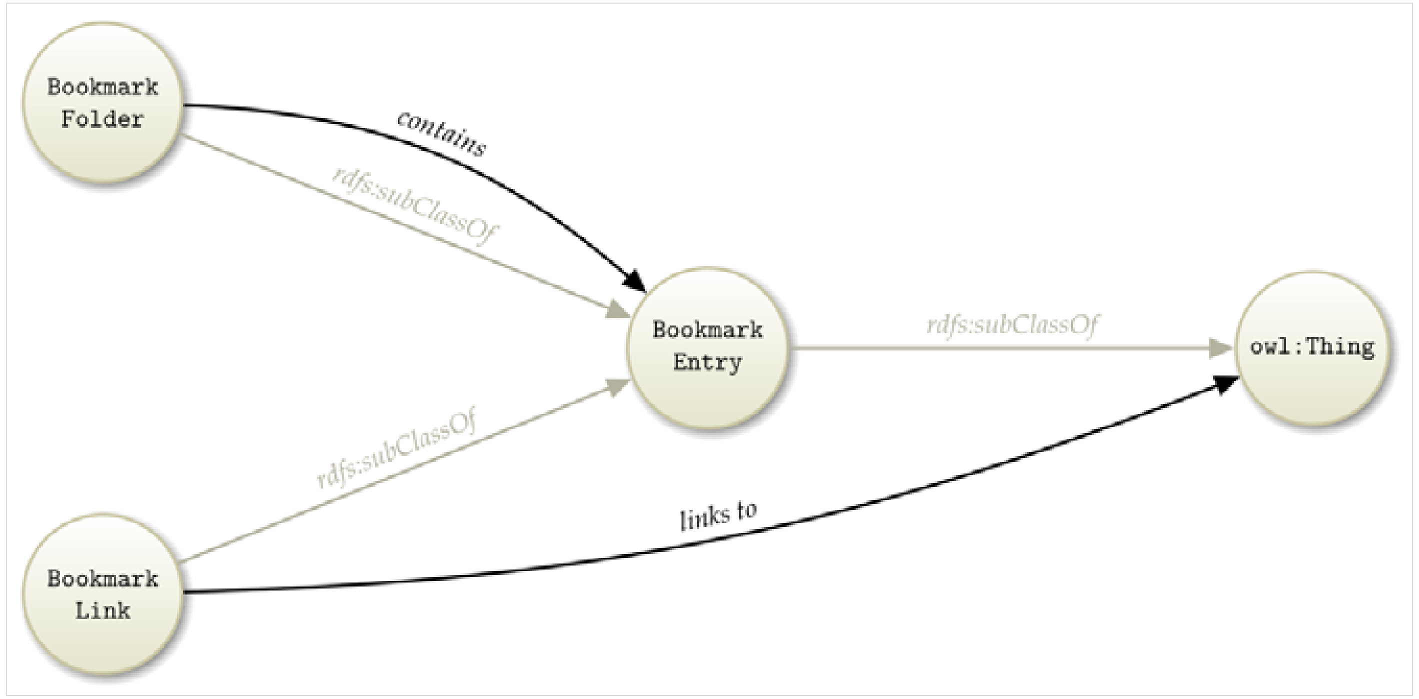
The ontology also models all data structures necessary for representing route cards. A route card describes the environment and necessary actions for salvaging cultural artefacts in the case of an emergency, including a classification and description of the artefact itself, its location (deploying the above concept of ROIs), and tools and actions for actual removal and transport of the endangered artefact. Route cards are used in the WALKER application. For more details on route cards and the WALKER application, see the corresponding section on the knowledge base server.

5.4 Bookmarks

Another feature of the ontology is support for managing bookmarks. Bookmarks are, just like ROIs, hierarchically organized in bookmark folders. Each bookmark folder can contain any number of bookmark entries, i.e. bookmark links as well as nested bookmark folders. A bookmark link is, in effect, just a link to any other object in the ontology (see Figure 11).

We use bookmarks to leverage access to related objects, e.g. to all elements of the set of 5 case studies that are documented in our semantic database. Another application of the bookmarks feature is a collection of 83 best practice examples of cultural heritage protection that we have collected.

Figure 11: Ontology model for bookmarks © Fraunhofer IOSB

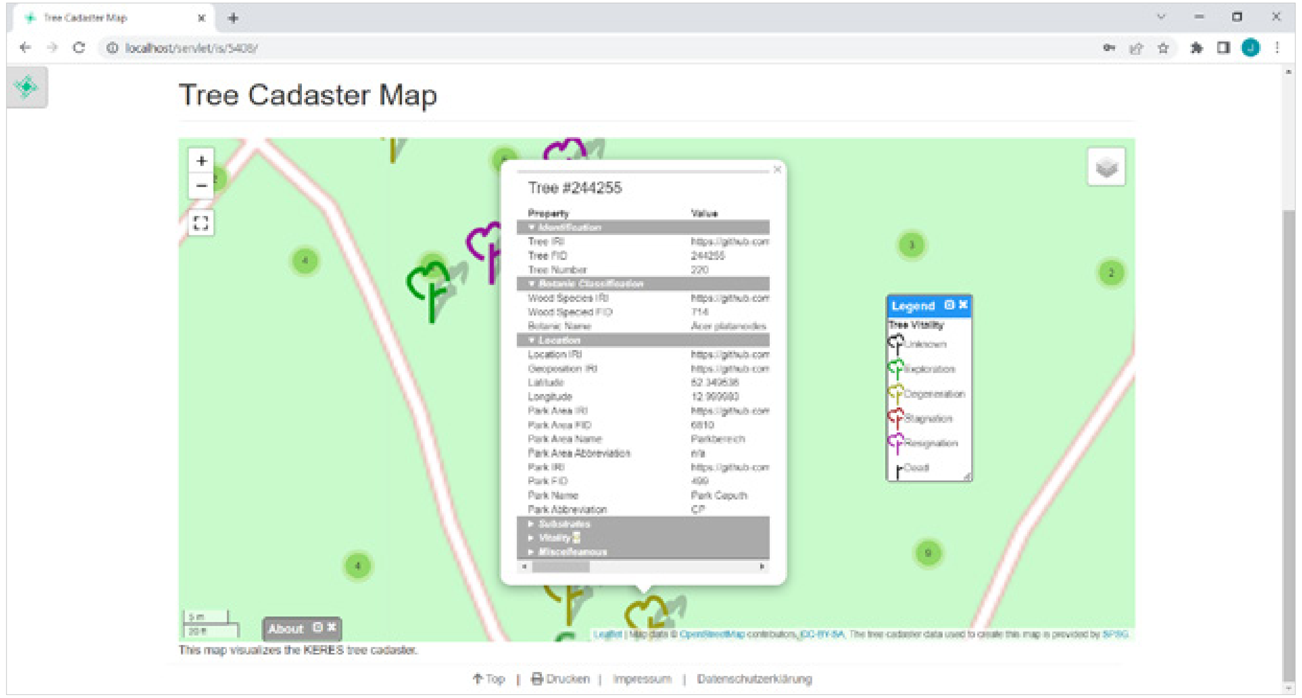


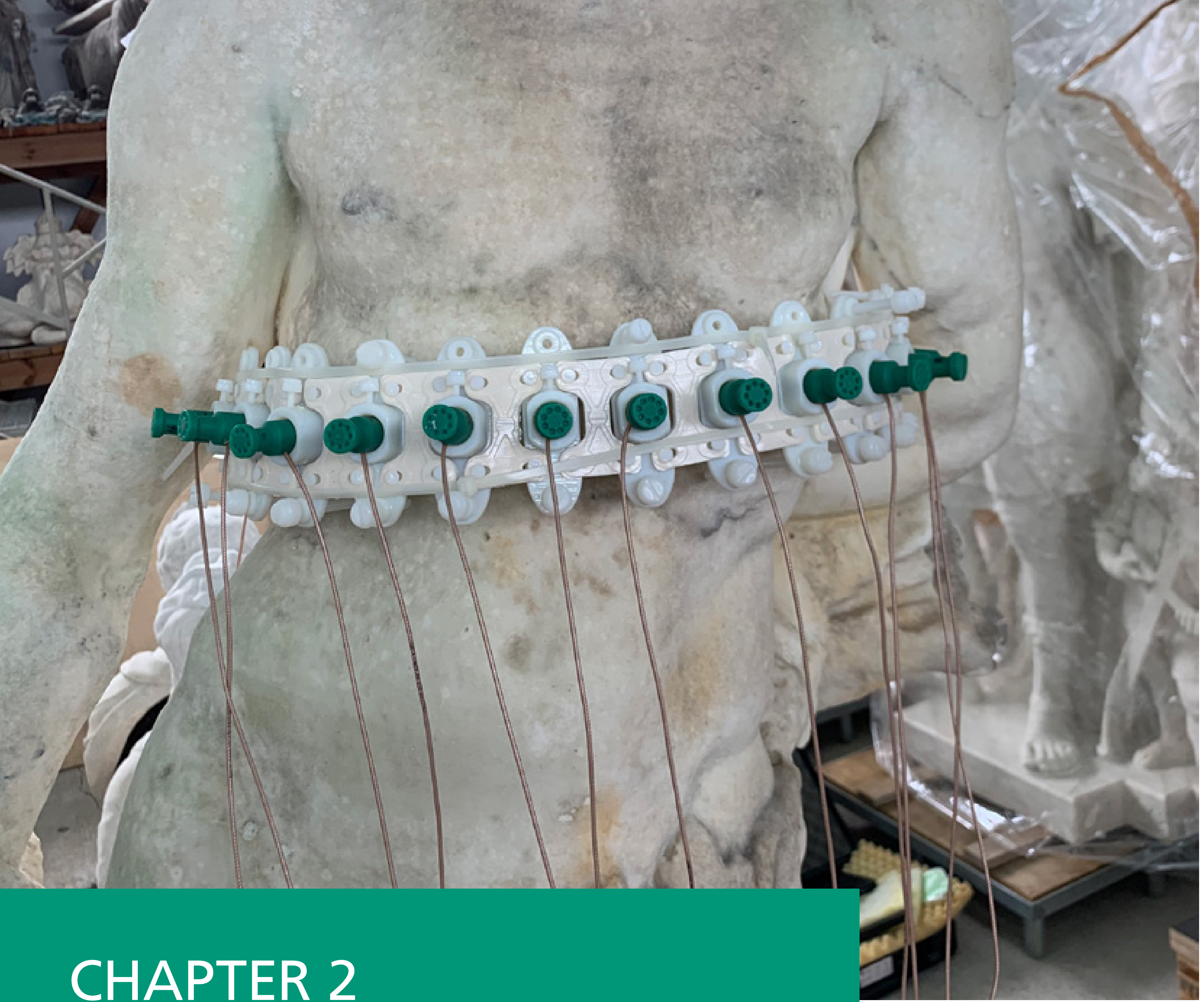
5.5 Tree register

Another, still experimental feature is support for modelling trees in a tree register. In this register, for each single recorded tree, we collect properties such as each tree's unique ID, its top diameter, its function by one out of 10 possible categories (such as avenue tree, big bush, or frame tree), as well as its vitality by one of 5 quantitative values (exploration, degeneration, stagnation, resignation, dead) or felling date, if applicable. Each tree can optionally link to a proper photo.

Trees in a tree register are typically associated with a park area that hosts them, with each park area being part of a park. Hence, park areas and parks are modelled as ROIs (see above), for mapping each park area to its enclosing park, and associating each park e.g. with its surrounding municipality.

Figure 12: The KERES tree cadaster © Fraunhofer IOSB





CHAPTER 2

DIGITAL TWINS, DAMAGE DETECTION AND MATERIAL ANALYSIS

1. DIGITIZATION OF CULTURAL ASSETS AND OBJECTS

Peter Weber (Fraunhofer IBMT)

In its Charter on the Preservation of the Digital Heritage, the UNESCO says: "The digital heritage consists of unique resources of human knowledge and expression. It embraces cultural, educational, scientific and administrative resources, as well as technical, legal, medical and other kinds of information created digitally, or converted into digital form from existing analogue resources. Where resources are "born digital", there is no other format but the digital object" (UNESCO, 2003).

Now, almost 20 years later, digitization of cultural assets and objects is daily business in many locations. On the background of climate change and accidental or malicious destruction, digitization of cultural assets and objects becomes one of the strategic procedures that transforms real objects as digital twins into a virtual environment. Using digital tools like simulations in the virtual world can enable and force the preservation and reconstruction in the real world as can be seen by the example of Notre-Dame in Paris (Veyrieras, 2019).

In the recently published "Report on a European collaborative cloud for cultural heritage" the authors ask: "Digitization technologies: a consolidated domain or further research needed?" (Brunet et al., 2022). They say clearly that the digital twin means more than creating a 3D model that represents the shape (geometry), colour and texture of an object. Additional technologies have to be used to capture a holistic representation, e.g. looking inside the objects analysing their material and internal structure. Of course, all the other intangible information available about provenience, history, destiny, etc. have to be included in the digital twin, but this chapter will focus on the generation of digital twins.

The Fraunhofer-Gesellschaft (FhG) with its numerous institutes provides a manifold of technologies, methods and services for the production of digital twins. Objects and assets can be digitized indoor and outdoor. Using different interfaces and tools, digital twins can be visualized and manipulated directly in virtual reality (VR) or as part of the real world in an augmented or mixed reality environment (MR, AR, Metaverse).

On the following pages technologies and methods will be presented, which were used in the FALKE I and II projects, starting with a few notes on digital twins. Different scan methods and methods for non-destructive diagnosis and material analysis will be described using examples from both projects. VR and AR technologies and methods to interact with the twins will be explained.

2. DIGITAL TWINS

Peter Weber (Fraunhofer IBMT)

The concept of the "Digital Twin" was developed at the beginning of the 21st century and introduced as a close concept in 2003 by Michael Grieves at the University of Michigan (Grieves, 2015). The initial idea was to create a digital (virtual) model of an existing object or system, which fully or partially represents the physics in the real world concerning appearance and functionality. The concept is an important part of the Industry 4.0 approach. The Digital Twin is used for simulation, control, maintenance, planning, development, etc. for the real system or object, and by the use of sensors and interfaces, an interaction of the real system and the digital twin can be enabled.

The concept was introduced to cultural heritage objects and assets recently and has shown its efficacy and power e.g. in the energy management of historic buildings (Massafra et al., 2022).
In the FALKE I project, the concept was used digitizing e.g. sculptures and consolidating their digital twin with extended information about origin, provenience, internal and external structure as well as material information (Weber, 2020). As in Industry 4.0, the digital twin of a cultural heritage object or asset is more than a simple digital object like a surface scan. It should be used in many cases for research, preservation, restoration and teaching or as a tool to curate exhibitions in the real or a virtual world. If possible, it should provide the ability to simulate the physical appearance and functionality of the real object including motion if available.

One question that arises with the concept of digital twin is the amount of data that is necessary to be processed. Not so much during the generation of the twin but when interacting with it in real time e.g. in virtual reality.

Other basic questions are:

- How to make the twin available (distribution)?
- Who should have access to what sort of information and functionality of the twin?
- How authentic should the twin be compared to the real object? This concerns resolution and data management and the question what degree of authenticity is necessary for what application.
- How about the copyright of the "original" digital twin? Will the concept of non-fungible tokens (NFTs) be implemented as it is of great interest now for "born digital" objects?

As can be seen from these few questions and of course there are more, additional discussion is necessary beyond the content of this text.

On the next pages those technologies of the Fraunhofer-Gesellschaft are described, which are necessary to create, to visualize, to interact with and to maintain the digital twin.

3. SCAN METHODS

3.1 Photogrammetry

Pedro Santos, Constanze Fuhrmann (Fraunhofer IGD)

In the mid-19th century, the theory of photogrammetry was being developed in France (Laussedat, 1899) and Prussia (Meydenbauer, 1867) in parallel with emerging photography. It was used for measuring buildings but also for land surveying. The first authority in the world to work photogrammetrically was the Royal Prussian Measuring Image Institute, founded in 1858. In 1909, the Carl Zeiss company commercialized the "stereo-autograph" invented 1907 by Eduard von Orel, which was used for the first time to automatically draw contour lines by optically scanning the photos (stereo image pairs) (Orel, 1938).

Photogrammetry is a passive, indirect method with which the entire surface visible to an optical sensor can be recorded by means of many overlapping images from different directions on an object. So-called "feature correspondences" are determined between overlapping images, for example pixels with the same intensity values in their surroundings, which indicate that they must come from the same point on the object surface. The 3D point on the object surface associated with this "feature correspondence" is then calculated via triangulation. A 3D point cloud is then created from many "feature correspondences", which is then covered with a triangular mesh to form a 3D model of the object. Photogrammetry can be used at any distance and is primarily dependent on the cameras and lens systems used, but also on the geometry of the stationing. Resolutions of 10 µm can be achieved and there are now systems that also record metallic and reflective surfaces without the use of matting sprays.

An example of the latest development using photogrammetry is the CultArm3D developed at the Fraunhofer IGD, a fully automated color-calibrated 3D digitization robot able to capture arbitrary objects at reproducible high resolution at the push of a button. The motivation for this digitization station is to relieve the human operator from tedious tasks, such as repositioning a camera around the object and keeping track of the digitization progress to

Figure 1: Three variants of the CultArm3D System for different digitization volumes

eventually ensure a complete surface coverage and stable quality. Those are challenging tasks even for expert digitization operators, especially for high resolution digitization where the scanner measurement volume (defined by the camera optics) is normally a lot smaller than the object itself, and thus the resulting high resolution 3D model is comprised of many single scans or images. The impact of this digitization station is twofold. Firstly, the overall digitization time is effectively reduced by a high data acquisition rate with automated and parallel processing. Secondly, the automated and adaptive data acquisition enables the economical use of focused camera optics, such as macro lenses, to the digitization task even for larger objects, and thus effectively increases resulting surface resolution and 3D model quality.

The CultArm3D digitization station (Figure 1) reconstructs 3D models using the established technique of photogrammetry. Therefore, the acquired raw data consists of high resolution photos of the object, covering each surface part several times, in order to use structure-from-motion (Gao et al., 2014; Özyesil et al., 2017) and multi-view-stereo (Goesele et al., 2010; 2007) techniques to recognize features and triangulate 3D information. In general, given a set of photos with complete surface coverage, then the higher the camera image resolution, the higher the resolution of the resulting reconstructed 3D model. Hence, for highest resolution focused camera macro optics can be applied even for objects much larger than the actual camera measurement volume (defined by field of view and depth of field) and capturing only a small part of the object surface per image but in high resolution (Figure 2). The drawback is that because of the small measurement much more photos are necessary to cover the complete surface. This trade-off between time and quality is addressed by this digitization station.

At the current state the CultArm3D digitization system captures a high resolution image in average every 4 seconds (approx. 900 images per hour). The images are directly transferred via USB3 connection and stored in a project folder for further processing. For small camera movements between views, e.g. during focus stacking, the system's acquisition speed becomes mostly limited by transfer speed of the camera. To achieve this high acquisition rate a state machine is modelled in software that synchronizes the different hardware and software components, such as camera, lights, robot arm and turntable, reconstruction, view and trajectory planning modules.

In this scope, view planning describes the process of computing a sufficient set of camera views with position and orientation that captures the object of interest as complete as possible resulting in a 3D model with the desired quality. This can be even an incremental process involving a feedback loop of planning, capturing and reconstructing, where the intermediate incremental reconstruction serves as the input for the next planning phase. It can be also regarded as an optimization problem, with the objective function of maximizing an overall model quality estimate while satisfying the safety constraints. The challenge however lies in the definition of a proper quality estimate that can be frequently evaluated during the scanning process and predicts / correlates with the desired quality of the final 3D model.

The CultArm3D features a hybrid approach that relies on little initial user input of setting a bounding and safety volume by defining a cylinder in height and diameter around the object on the turntable. Then a first set of approximated views can be quickly calculated and carried out mainly based on the volume size, the camera field of view and focus distance. Figure 2 shows the intermediate reconstruction result from an initial quick scan with 40 images reduced to low resolution. The point cloud density is automatically evaluated and low density areas and holes are identified (and highlighted with red color) and can be distinguished from areas with sufficient density (blue color).
Based on the intermediate 3D reconstruction, a second more detailed set of views is planned utilizing rendering technologies and the calibrated camera intrinsics to simulate the effect of each view candidate.

Figure 2: CultArm3D – Depth of field estimation of two camera view candidate (green: optimally focused, blue: far plane, red: near plane)

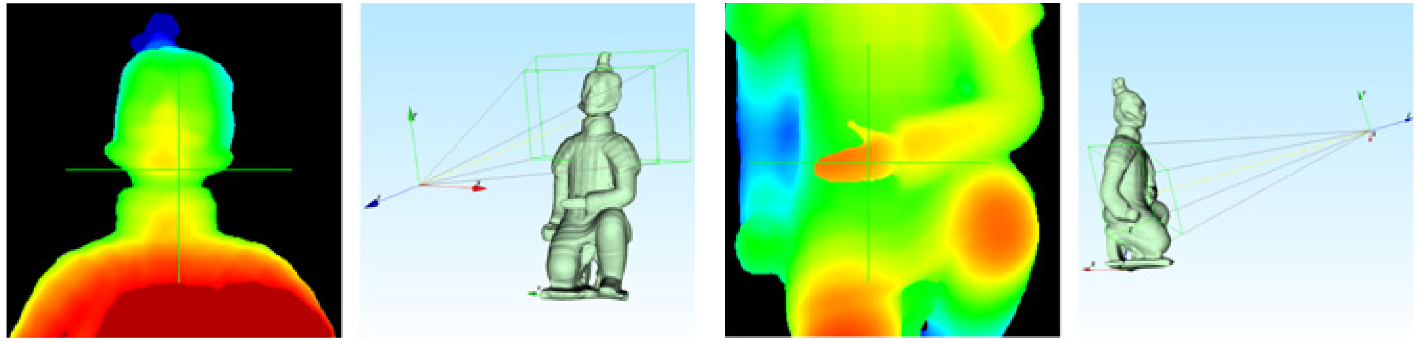


Figure 3: Reiss Engelhorn Museums – JAVA Gold Exhibition: Earring with mythological Daemon, Java 14.- 15. AD © CES / 3D-Model: Fraunhofer IGD

In comparison to other 3D reconstruction techniques, such as structured-light or space-time analysis for laser triangulation, photogrammetry is computationally expensive, normally resulting in long processing times of several hours for the final full resolution model. Therefore, the final 3D model in highest quality based on the full resolution images is usually calculated offline after the data acquisition process with the automated digitization station finished (Figure 3). In order to predict an adequate reconstruction quality for the final model and ensure complete surface coverage, intermediate low quality 3D models are reconstructed in clusters already during the digitization task and serve as a quality indicator and decision base for further digitization actions.

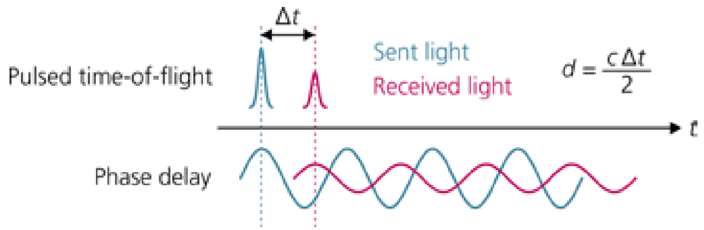
3.2 Photogrammetry and LiDAR

Lisa Rentschler (Fraunhofer IPM)

There exist numerous technical possibilities for the three-dimensional mapping of large and complex structures. Among those are image- and LiDAR-based (Light detection and ranging) methods. Since both can generate high-resolution digital twins, they allow to preserve cultural heritage in digital form. Here, the application of these methods will be demonstrated based on the example of the historic Wasserschlösschen in Freiburg.

At first a little insight into the LiDAR measurement principle: The different methods are often divided into two categories – the pulsed time-of-flight and the phase-delay measurement (see Figure 4). Both methods have in common that they measure the round-trip time of laser light to an object. The constant speed of light now acts as a ruler and allows the conversion of the time delay into a distance. In case of the pulsed time-of-flight method, a very short light pulse (typically in the range of a few nanoseconds) is emitted from the device. The time delay Δt can be directly obtained from the time shift between the sent and the received pulse. This method has the advantage that it can detect multiple echoes in a single measurement which often happens at object corners where only part of the laser spot hits the first object. However, this capability often comes at the cost of reduced accuracy. In contrast, the phase-delay method uses periodically intensity-modulated laser light instead of a single light pulse. With modulation frequencies in the range of several hundred megahertz the time delay Δt can be precisely obtained from the phase shift between the sent and received wave. While this method typically delivers the better accuracy and measurement speed, it lacks the ability to tolerate multiple reflections. In order to obtain areal measurements, both methods are usually combined with fast beam deflection units which scan the laser beam into different directions and allow point-cloud generation of large structures within minutes. Depending on their intended use case, the scanner systems are available as hand-held devices, tripod-mounted terrestrial scanners or mounted on mobile platforms, e.g. vehicles like cars and trains, installed on unmanned aerial vehicles (UAV) or even optimized for subsea operations.

Figure 4:
Illustration of pulsed-time-of-flight and phase-delay distance measurement. The object distance d can be deducted using the time delay Δt and the speed of light c.
© Fraunhofer IPM



During the Falke II project, four different LiDAR systems were compared: a terrestrial scanner by Faro, a terrestrial and a hand-held scanner from Leica Geosystems, as well as the clearance profile scanner (CPS) developed at Fraunhofer IPM which is mounted on a mobile urban mapping (MUM) vehicle (see Table 1).

The 3D point clouds acquired with these LiDAR-systems were complemented by photogrammetry-based point clouds (see Chapter "Photogrammetry") from a handheld camera by Fuji and an airborne system by dji.

The Wasserschlösschen in Freiburg was chosen as test object. This building is a historic water reservoir that disguises its profane interior with a front in the style of a small castle. It was built in the late 19th century and is located at the forest line on the outskirts of Freiburg. Its detailed design and material mix of sandstone and cast stone provides a variety of surfaces which makes it an ideal choice as a test object. Because of the location near the forest with its many walkways and its use as communal water tank, legal permissions had to be acquired in advance of the measurement campaign, this is particularly relevant for the airborne based data acquisition. Besides technical difficulties like ambient light, GNSS reception strength or weather, one is confronted with some practical aspects as the measurements take place in public space: pedestrians can block the clear view onto the object and the technical equipment might attract the attention and raise critical questions the team should be prepared for. With all preparations done, the Wasserschlösschen was scanned and photographed using the following equipment:

Device	Manufacturer	Measurement method	Type
Focus 3D S 120	Faro Technologies Inc.	Lidar, phase measurement	Terrestrial laser scanner (with integrated cameras)
Clearance Profile Scanner (within the Mobile Urban Mapping system)	Fraunhofer IPM	Lidar, phase measurement	Mobile laser scanner (with integrated cameras in the MUM system)
RTC360	Leica	Lidar, pulse measurement	Terrestrial laser scanner enhanced with waveform digitizing (with integrated cameras)
BLK2GO	Leica	Lidar, pulse measurement	Hand-held laser scanner enhanced with Waveform Digitizing (with integrated cameras)
X-T10	FUJIFILM	Photography	Digital single lens mirrorless camera
Phantom 4 Advanced	DJI	Photography and Video	UAV Camera
GS16	Leica	RTK GPS	GNSS smart antenna

Table 1: List of used devices © Fraunhofer IPM

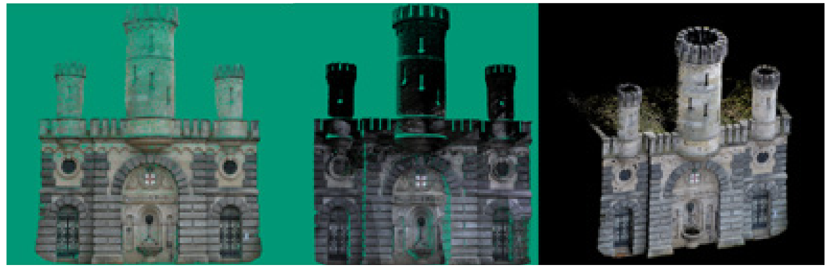


Figure 5:
Photogrammetric (left) and scanner data (center) were combined into a highly detailed 3D point cloud of the Wasserschlösschen (right).
© Fraunhofer IPM

In the first measurement campaign (10/2020) the Faro Focus 3D S 120 was used on three positions located about ten meters away from the front of the building. The scanner was configured with a point-spacing of 1.2 cm and its highest quality setting. For proper initialization of the GNSS system the MUM system had to be started in advance of the actual measurement of the Wasserschlösschen which generated about 300 GB of data – including high resolution images. This allowed the fusion of distance and image data into a colorized point cloud.

The recorded data from the FUJIFILM X-T10 and the dji Phantom 4 Advanced were photogrammetrically processed using Regard 3D (opensource) and Metashape (Agisoft) to generate colored point clouds.

For geo referencing the point clouds to the ETRS89/UTM coordinate system, several ground-control points were mapped by the GNSS-Rover and incorporated via CloudCompare (opensource) in the processing of the clouds. The result is shown in Figure 5.

In the second campaign (04/2022) the Leica RTC 360 was used on ten different positions also located about ten meters in front of the building with its best point spacing setting of 3 mm in 10 m distance. The measurements were complemented with the Leica BLK2Go – a handheld scanner which tracks its movement using integrated cameras and a SLAM algorithm (simultaneous localization and mapping). The building was circled from front to front to create a closed measurement path which is beneficial for the SLAM-accuracy. This generates different measurement perspectives effectively preventing shaded areas. Those two systems also generate RGB information for the resulting point clouds with their integrated cameras.

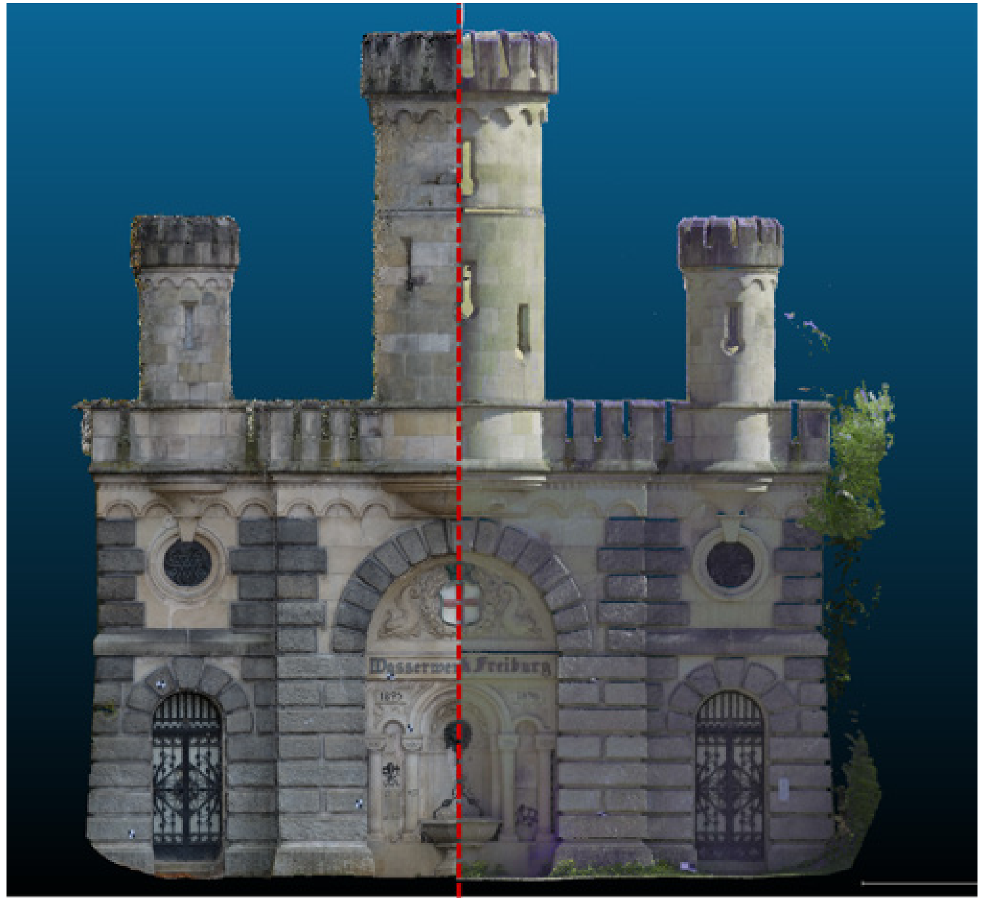
A second aerial scan was performed with the dji Phantom 4. Two automatic flights based on predefined GNSS waypoints, and one manual flight resulted in 367 images which were also photogrammetrically processed with Metashape (Agisoft) to generate a colorized point cloud (see Figure 6).

Figure 6:
Individually generated 3D point clouds with (from left to right):
1. data from the handheld scanner (BLK2GO),
2. photogrammetric data captured with the Phantom 4,
3. data from the terrestrial scanner (RTC360)
© Fraunhofer IPM

Both campaigns provided four 3D point clouds of the Wasserschlösschen generated by laser scanning and three 3D point clouds generated by photogrammetry. The individual measurements of the two campaigns were fused into two point clouds. One showing the building in October 2020 and one in April 2022 (see Figure 7). On this basis, the measurement techniques and equipment can be compared to differentiate between optimal operational areas. As for the initial question of usage for the protection of cultural heritage in times of the climate crisis, the measurement campaigns not only provide digital three-dimensional twins of the building, but also show the applicability of the different devices to monitor changes or possible degradation of cultural landmarks in comparison over a specific time. This serves the preservation of cultural heritage by allowing an objective assessment of the actual condition.

Further, the digital twins can easily be made available to the public.

Figure 7:
Side-by-side comparison of the first (left) and second (right) measurement campaign
© Fraunhofer IPM



3.3 X-ray

Theobald Fuchs (Fraunhofer EZRT)

Soon after World War 2 first inspections of musical instruments by means of X-ray imaging were undertaken. Until the beginning of the 1990ies most examinations were restricted to straight forward radiographs showing a two-dimensional shadow image of the object irradiated with X-rays, a so-called projective image or projection.

Later, more and more researchers succeeded in three-dimensional imaging of historically relevant objects e.g. mummies, early clocks, statues, musical instruments, relics and various art work by utilizing medical CT systems.

However, medical CT, as its objective is the examination of the human body, has some disadvantages if applied to most other man-made artefacts: the spectral distribution of the radiation in combination with the X-ray tube's electrical power is most often insufficient for the required metrological precision and the combinations of materials. As well the spatial resolution achievable with medical CT hardware (typically around 0.3 mm) cannot fulfil requirements posed by conservational or analytical applications like for instance dendrochronology. In addition, the size of the objects may exceed the maximum receivable size of a medical scanner.

Thus, although medical CT is a widespread technology, fast and easy to handle for the trained personnel in hospitals or practices, industrial CT is clearly the choice as 3D X-ray imaging modality in research on cultural heritage. Industrial CT overcomes the mentioned deficiencies, although it is relatively slow. Scan and reconstruction can take a few minutes up to several hours, since due to the physics of X-ray imaging in three dimensions time increases with the third power as the spatial resolution element decreases.

During a medical CT, objects rest on a CT bed while source and detector rotate around it. In contrast, industrial CT requires a stable mounting system to position the object in an upright orientation on a rotary table between the source (an X-ray tube) and digital detector array (a semiconductor flat panel matrix, see Figure 8).

Essentially, industrial CT has three major features that allow for high-precision, high spatial resolution imaging of most man-made objects, instruments or tools:

1. Higher voltages applied to specialized X-ray tubes. Typically with more than 200 kV or even up to 600 kV, the radiation's energy is sufficient to penetrate several millimeters of technical metals, silver, gold or even thin sheets of lead.

2. The X-ray sensors, so-called flat panel matrix detectors, which are implemented in a CT system deliver images with ten times better spatial resolution compared to the multi-row-detectors built in medical CT gantries.

3. The distances between the rotational stage, where the object under examination is positioned and the X-ray source, respectively, the X-ray sensor can be varied mechanically within a wide range. This allows for setting an optimal data acquisition geometry depending on each individual object that is due to become inspected.
   In consequence, the spatial resolution achieved in the final volume image can be tuned according to the user's requirements. Sometimes, under certain circumstances, details with a size below 1 µm (one thousandth of a millimeter) can visualized.

A challenge, which medical and industrial CT have in common, is the increasing tendency for image distortion by artifacts if materials with very different densities (e.g. metals vs. organics) are present in the investigated object. These distortions can be mitigated in industrial CT by utilizing dual-energy-techniques and sophisticated image reconstruction methods, that are relatively time consuming but effective.

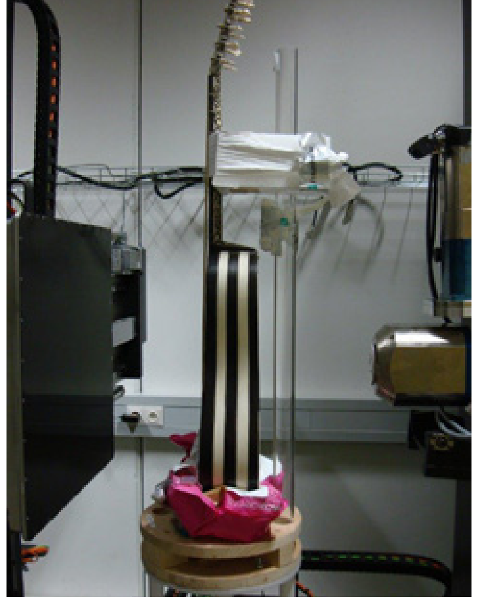


Figure 8:
A guitar (Germanisches Nationalmuseum, MI58) prepared for scanning on the multifunctional mounting system. The instrument is fixed on a rotational table (center) between the X-ray source (metal tube case, right) und the X-ray imaging sensor (black square, left). While the object is rotating slowly in the X-ray beam, several hundred up to thousands of images are recorded and processed afterwards by the image reconstruction computer, which calculates the three dimensional volume image, the so-called "voxel data set".
© Germanisches Nationalmuseum, Nürnberg

3.4 Terahertz and Millimeter Waves

Maris Bauer, Fabian Friederich (Fraunhofer ITWM)

What is terahertz?

The terahertz frequency region is situated in the electromagnetic (EM) spectrum between microwaves and the infrared region and is commonly defined for electromagnetic waves with frequencies from 0.1 to 10 THz (see Figure 9).

This spectral range is of particular interest for contactless, non-destructive measurement scenarios due to the special characteristics of the terahertz waves. The waves can penetrate most materials with no or only weak electrical conductance and can thus yield information of hidden internal structures of investigated objects. At the same time, the energy and typical power levels of terahertz radiation are low so that no damage via ionization or heating occurs. This also makes terahertz technologies safe to be employed by human operators and in highly-sensitive environments. Finally, the typical wavelengths of radiation in the terahertz frequency region extend from several millimetres – the spectral region from 0.1 to 0.3 THz is therefore often called the millimetre wave region – down to some tens of micrometres. These wavelengths define the minimum lateral resolution in terahertz imaging and match well with relevant spatial dimensions in many typical application contexts. In general, the trade-off in terahertz imaging is commonly between a desired image resolution and the feasible penetration depth at the corresponding wavelength.

Because of the combination of the above key features, terahertz technologies are in particular suitable for the volumetric investigation of highly sensitive materials for hidden internal structures and/or damages, e.g., often unique objects in the context of cultural heritage (Bauer et al., 2022).

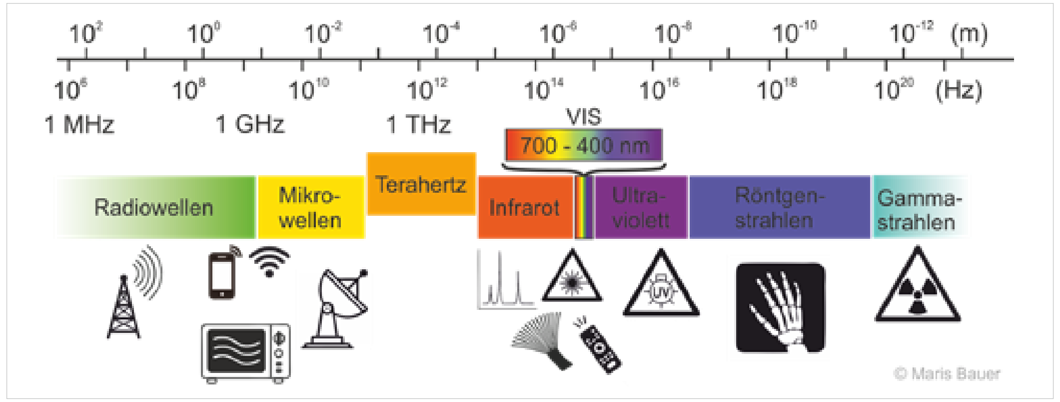


Figure 9:
Electromagnetic (EM) spectrum with wavelength in meter (m) and frequency in Hertz (Hz)
© Maris Bauer

Terahertz measurement methods

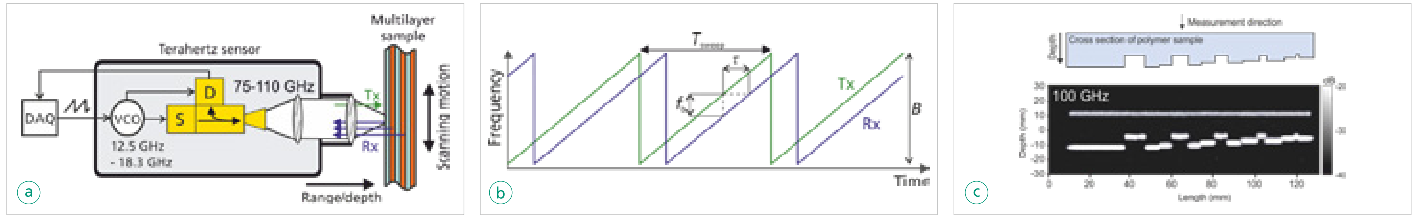
Terahertz technologies for non-destructive testing applications can in general be divided into two technological branches related to the generation and detection of the radiation. Being situated between the microwave and infrared regions of the EM spectrum the terahertz region can be accessed with technologies from either side, i.e., electronic microwave circuits on the lower frequency end and optical, laser-based technologies on the higher frequency end. The two most prominent approaches in the application of terahertz waves will be addressed below.

Frequency-modulated continuous wave (FMCW)

Approaching the terahertz region from the lower frequency end, established techniques from microwave electronics can be implemented to extend into the millimeter wave and terahertz frequency ranges. The basic principle of the approach is to generate typical high-frequency (HF) signals in the range of several tens of GHz via well-known and widely available integrated oscillator circuits. The output frequencies are then amplified and frequency-multiplied into the terahertz region with the help of nonlinear circuit elements, commonly diodes. The exact design and implementation of these multiplier chains determines the final output powers and available tuning bandwidths of the terahertz systems.

A measurement technique for the acquisition of 3D volumetric terahertz images is the so-called frequency-modulated continuous wave (FMCW) radar technique. Figure 10a illustrates a typical terahertz transceiver setup using the FMCW measurement principle (illustrated in Figure 10b). Terahertz sources based on electronic components are usually laid out to work with so-called continuous wave (CW) signals, i.e., signals oscillating at a single frequency (as opposed to frequency broadband, pulsed signals). Nevertheless, the specific frequency of the CW signal can be tuned, e.g., using a voltage-controlled oscillator (VCO) as the initial stage of the multiplier chain, whose precise output frequency is determined by an applied DC voltage. A data acquisition unit (DAQ) drives a VCO with linear analog voltage ramps, which in turn yields linear frequency sweeps at the VCO's output (here from 12.5 to 18.3 GHz). In a multiplier chain (S), the frequency ramps are multiplied into the terahertz frequency range (here with a factor x6 to 75 to 110 GHz). The terahertz radiation is then transmitted (Tx) to a sample under test, commonly guided and focused via quasi-optical beam forming with appropriate lenses or mirrors. Non-conducting materials are penetrated and at each material interface – i.e., changing terahertz index of refraction – within the sample, a partial reflection of the signal back to the FMCW transceiver occurs. These received Rx signals are time shifted with respect to reference Tx signals by a time τ due to the time of flight of the radiation to the sample and back. When Rx and Tx signals are frequency-mixed

Figure 10:
(a) Illustration of terahertz FMCW transceiver © Fraunhofer ITWM, published in Ellrich et al., 2019
(b) FMCW measurement principle © Fraunhofer ITWM, published in Ellrich et al., 2019
(c) Terahertz line scan (B-scan) at 100 GHz of a polymer test sample with bore holes at the rear side © Fraunhofer ITWM



– e.g., in a diode-based receiver (D) – the mixing product is a difference frequency f_{diff} which can directly be recorded with the DAQ. A simple relation directly translates the recorded difference frequencies to the time delays and thereby the distance d travelled by the terahertz waves:

$$d = \frac{c}{2n}\tau = \frac{c}{2n}\frac{f_{diff}\ T_{sweep}}{B}$$

Figure 10c shows an exemplary terahertz depth profile along a single line across a polymer test sample. As the terahertz waves can penetrate the whole sample, strong reflection signals from the flat front side and at the same time several steps and bore holes at the sample's rear side are revealed in the terahertz image. Finally, the measurement system is, e.g., raster-scanned over an object in order to obtain a full volumetric terahertz image of the sample. With the transceiver shown in Figure 10, typical image resolutions of approximately 3 mm in lateral dimensions and 4 mm in depth – determined by the available frequency sweep bandwidth – can be achieved. Similar measurement systems working at higher center frequencies can yield higher image resolutions, for example of approximately 1 mm in both lateral and range directions with a 300 GHz terahertz transceiver.

Time-domain spectroscopy (TDS)

Another terahertz measurement principle approaches the frequency region with technologies from the optical/infrared region. In the so-called time-domain spectroscopy (TDS) technique, ultra-short laser pulses are converted into typically picosecond-long, short terahertz pulses covering large bandwidths of several THz. Similar to the FMCW technique, the terahertz radiation is guided to an object under test and reflected inside a sample at interfaces of different refractive indices. Since TDS system are inherently working in the time domain, a direct measurement of the time of flight of the individual terahertz pulses is obtained, which again directly corresponds to a distance information. TDS systems, in general, provide less output power than electronic FMCW transceivers and the penetration depth into thicker materials can often be limited due to signal attenuation inside a sample. On the other hand, the high precision of the measurement technique – a consequence of the huge bandwidth of the generated terahertz pulses – allows very high depth/range resolutions in TDS system of down to several micrometers of layer thicknesses. Therefore, TDS systems are often applied when thin samples are to be investigated and where a high depth resolution is desired to discriminate individual material layers. Typical application scenarios are the investigation of paint layers in both industrial environments (Ellrich et al., 2019) but also in the context of cultural heritage, e.g., thin paint layers of paintings (Fukunaga, 2016; Fukunaga et al., 2020) or surface layers of wood figures (Stuebling et al., 2020).

3.5 Microscopy

Erich Jelen (Fraunhofer UMSICHT)

Microscopy is a well-known method to look on the surface of a material or an object. Depending on the type of microscope, you will get different information. In the field of cultural heritage, microscopy can help to detect e.g. cracks or changes of surfaces. Stand-alone units are used in the lab, and mobile equipment can be used in the museum and the workshop.

Digital microscopy

A digital microscope is a type of inspection and measurement technology that is equipped with zoom lenses, an imaging device, usually a CCD or CMOS sensor. The image collected by the camera is displayed in real-time mostly on a built-in LCD monitor, therefore making it useful for R&D, quality, failure analysis, manufacturing-based and even restoration applications.

In order to display an image with a digital microscope, an image sensor with a color filter converts the light received from the lens into digital signals.

After processing those signals, the data are then converted into an image and displayed on the screen.

For field measurements, mobile lenses, shown as part A in the picture above, are very useful for non-contact measurements of the objects.

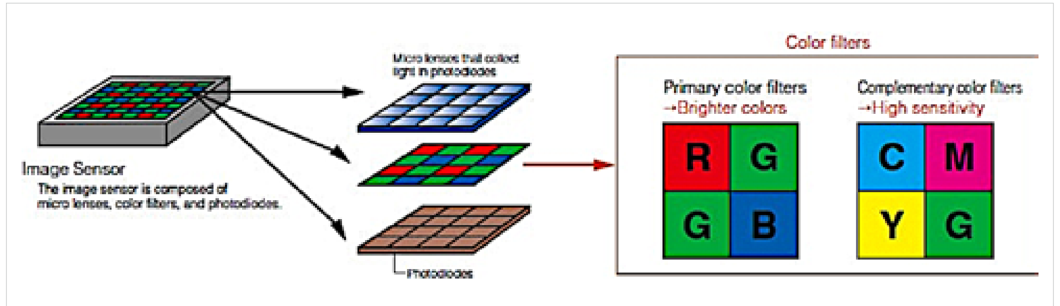


Figure 11: Mechanism behind the image sensor © Keyence

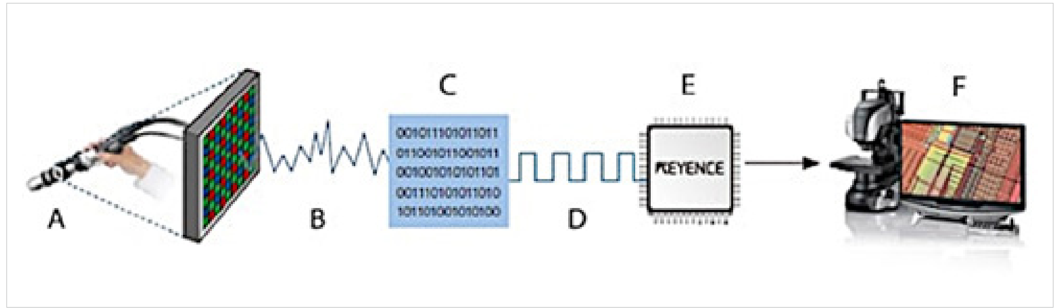


Figure 12: Mechanism behind the creation of digital images © Keyence

Confocal microscopy

The main difference between digital and confocal microscopy is the fact, that confocal microscopy generates real height data and not only pictures.

Using confocal microscopy was driven by the attempt to characterize the surface of wooden objects after decontamination with supercritical carbon dioxide or laser cleaning. The question was, if there were any impact on the surface using this cleaning methods. Scanning electron microscopy (SEM) could have given good answers, but the specimens are damaged caused by preparation or high energy impact and cannot be used for further chemical or spectroscopical analysis. SEM samples have to be small enough to fit on the specimen stage and may need special preparation to increase their electrical conductivity. Non-conducting materials are usually coated with an ultrathin coating of electrically conducting material (e.g. gold, graphite), deposited on the sample by low-vacuum sputter coating.

The 3D confocal microscopy is an optical instrument for measuring and analyzing surfaces. It can be used for DIN EN ISO compliant roughness determination, analyses of 3D structures, layer thickness and measurement of geometry in the micrometer and nanometer range. A wide range of materials from polymers to metals up to composite materials, all surfaces can be transformed into precise measurement data. The advantage of this kind of microscopy is that in most cases no sample preparation is required for measurement.

Basically, the method works on the principle of focusing a standard light microscope. As the microscope "scans" the surface, it moves the objective lens up and down to keep the surface in focus.

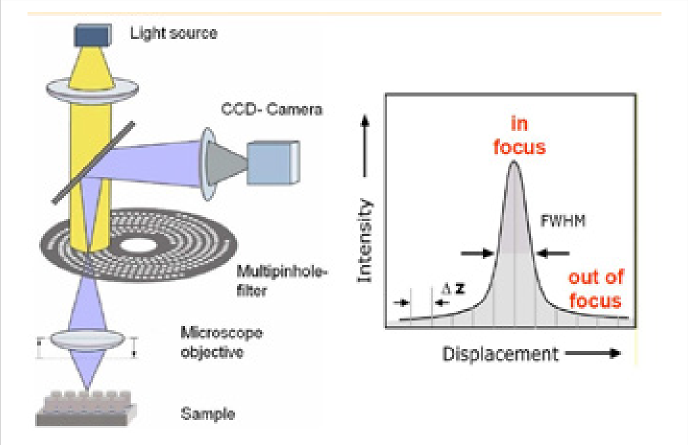


Figure 13: Principle of confocal beam path © nanofocus

This up-and-down movement is the change in height of the surface, the topography or roughness, which is then automatically stored. All height data are summed up and put together to create an error free 3D picture of the sample.

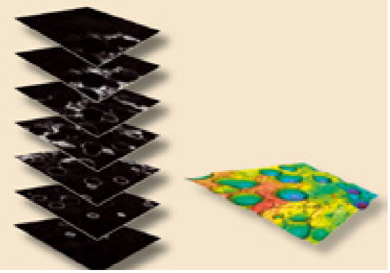


Figure 14: Image stack and resulting 3D topography © nanofocus

Within one measurement, all data for creating different analysis are stored:

- height,
- reflection,
- roughness,
- profile,
- three dimensional picture.

All reporting can be done at any time after the original measurement because all data are stored within the measurement.

3.6 Current state and methods of digitization in the museal field – a survey of 11 German museums

Erell Le Drezen, Thomas Rauch, Theobald Fuchs, Vanessa Jelito, Cansel Erdogmus, Wiktoria Humanicka (Fraunhofer EZRT)

In the last 20 years human life and its tracks have been documented more accessible than ever thanks to the spread of internet access and digital tools. To benefit researchers around the world and due to growing numbers of military conflicts, natural disasters, restitution processes and the enormous challenge of climate change, museums have decided to start backing up their collections digitally.

Taking in these considerations the Exploration Group of the Development Center X-ray Technology EZRT of the Fraunhofer IIS decided to survey 11 German museums and educational institutions on their progress in digitization. We tried to determine the interest in 3D digitalization, which methods are employed and what kind of financial resources the museums have available.

Methodology

The Exploration process of the Development Center X-ray Technology EZRT of the Fraunhofer IIS is an intrapreneurship process within which ideas for research and industry projects are tested for customer need, rentability and feasibility in a structured manner. The process is built on the principles of Lean Startup methodology as described by Eric Ries in 2011 and the testing of business hypotheses as described by Alexander Osterwalder in various works. For our process we adjusted these principles in a way that is more suited to the specific context in which Fraunhofer operates.
After the idea of digitization in the museal field was fed into the Exploration process, the most critical hypothesis was formulated as:

> H_1: Museums and similar Institutions are interested in digitizing their collections.

Doing guided interviews with experts from the museums sector was the most promising way of testing this hypothesis. The experts were previous contacts established through joint projects. We decided to follow the principle of the mom-test in accordance with Fitzpatrick (2016) when drawing up the interview guideline. Additionally, we employed methodology from empirical social studies in accordance with Helfferich (2019) and Porst (2019). The next step was to contact our chosen experts via email. We decided to reference previous projects and communicated the intent of our interview series. By doing so we were able to achieve a response rate of 73%.

For the interviews we decided to have one person doing the interview and one person in charge of recording the answers. Additionally, we employed an already established contact to have the experts be more at ease and to be able to give more context. During the interviews, we perceived a need for additional questions, which would affect the consistency of the findings. However, after accessing with the team, it was determined that adding questions would still be in accordance with the goal of the study. The answers were paired up with the corresponding questions. Any additional information was recorded in a separate section.

After concluding the interviews, we analyzed the answers based on our protocols. First the answers were transferred to an Excel spreadsheet, where they were shortened in a concise manner. Then we looked for similar answers which we categorized. Since the answers were from a qualitative interview, we decided to treat them as nominal datasets. For the graphical analysis we used bar charts and counted the response frequency. We settled on not doing any statistical analysis since the sample n=11 was too small to get any significant results.

Results

Our survey showed that ten out of the eleven institutions are taking steps to digitize their collections. However, these steps range from inventory lists in excel to publicly available databases with pictures and 3D datasets.

Employed methods	Frequency	Additional information
Photography	8	Due to low cost and effort
3D surface scans	5	
CT scans	2	However, one additional museum reported having bought a CT machine, which was not in service at the time of the interview
Excel	2	Registration of object history, origin and additional information
Digital dataset	1	Not specified
Audio recording	1	
Not specified	2	

Table 2: List of used devices

The reasons for digitizing were as follows:

Reason	Frequency	Additional Information
Research	5	Access for researchers and generating new scientific data
Preservation	4	
Taking Inventory	4	
Transparency	3	
Public relations	3	
Overview	2	

Table 3: List of used devices

The biggest challenges in implementing digitization projects were:

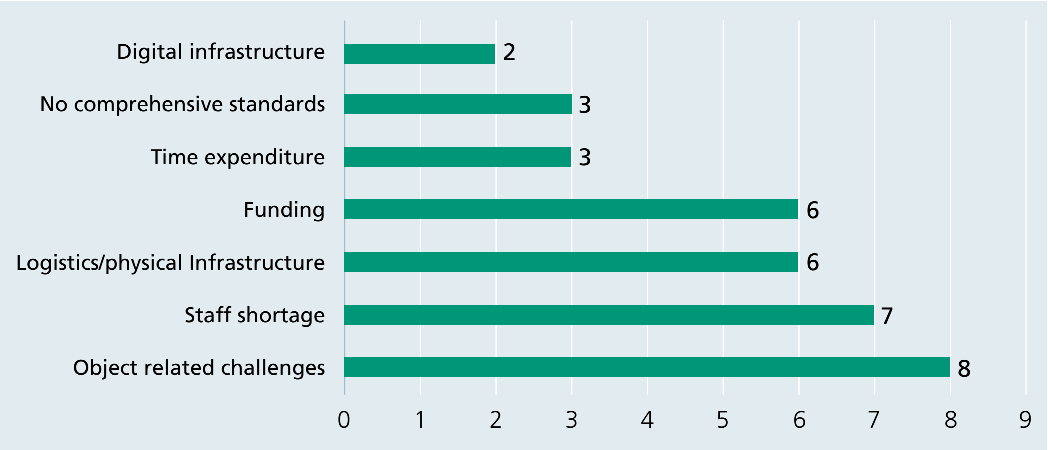


Figure 15: Biggest challenges © Fraunhofer EZRT

During the interview series, museums stated object related challenges as their biggest challenge. This category includes size, fragility and material. Staff shortages are second, museums note that shortage of staff tends to coincide with lack of funding. The survey revealed that museums are primarily funded by the state and research funding. Private funding tends to take the backseat. Logistics and physical infrastructure are next. They include lack of rooms, difficult transportation routes and lack of communication between departments. Furthermore, museums note that time expenditure is a challenge due to the sizes of their collections. The interviewees also expressed the need for overarching comprehensive digitization standards. And lastly, two institutions noted the lack of digital infrastructure, like IT departments and servers.

In the second half of the interview, we tried to determine the need and utility of 3D datasets. Museums consider public relations as one of the more important uses. This includes accessibility for people with disabilities, the possibility of open access databases and tools for citizen science projects. Research is considered just as important. Museums noted the possibility of online access for researchers and generating new research. Manufacturing replicas for exhibitions and museums shops can also be one of the uses. A commercial use is considered secondary. On further questioning the interviewees answered that using data commercially might be limited due to legal restrictions for public institutions.

Conclusion

We have shown, that digitization is an interest point for almost all surveyed museums. Steps are being taken to implement said digitization, although there is a lack of a uniform procedure and comprehensive standards. Research and preservation of collections seem to be the most important factors for implementing. However, museums are faced with challenges like lack of funding, object related challenges, lack of staff and time expenditure among others.

Therefore, we suggest offering museums a time effective and object specific solution for digitizing large collections. Supporting museums in finding a comprehensive standard for digital archives and in acquiring funding should accompany the offerings to museums.

Further research should go into further use cases for the digitized collections as well as the specifics of the desired digitization solutions.

4. DAMAGE DETECTION AND MATERIAL ANALYSIS

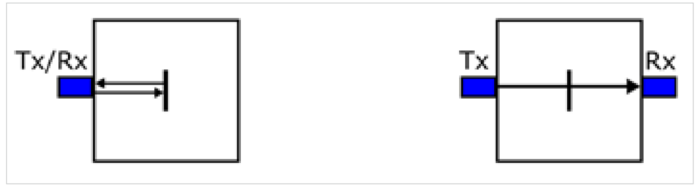
4.1 Ultrasound based non-destructive testing (ultrasound tomography)

Peter Weber (Fraunhofer IBMT)

Since more than 70 years, the use of ultrasound for non-destructive testing is a well-established technology. At the beginning of the 1980s, the technology was introduced for the diagnosis of sculptures made of marble or other stony materials. As in medical diagnosis, ultrasound is used to look inside the sculptures. Scope of interest are cracks, weathering, reinforcement and material properties. Especially for marble, it is important to get information about the material condition under the surface of a sculpture. Compared to other material marble is weathering from inside out due to the crystalline structure of the material. I.e. a sculpture might be close to collapse although the outer surface looks very "healthy".

There are mainly two methods that are used to examine sculptures or parts of historic buildings. The first one is the pulse echo method and the second one is the transmission mode (see Figure 16). In pulse echo mode the transmitter Tx emits a pulse into the object. Echoes are generated by internal structures and reflected back to the probe, which has switched to receive mode (Rx). In transmission mode the emitted pulse is received by a receiver which is located e.g. on the opposite side of the object. Both methods can be used to get information about the internal structure and condition of the object.

Figure 16: Pulse echo and transmission mode © Peter Weber, Fraunhofer IBMT



If the speed of sound of the material inside the object is known, the position of the structure can be measured from the travelling time of the echo. The transmission method can be used to measure the speed of sound of the material inside the object if the distance between the two probes is known and the travelling time is measured.
The latter method is the key for the technology of ultrasound tomography (see Figure 17).

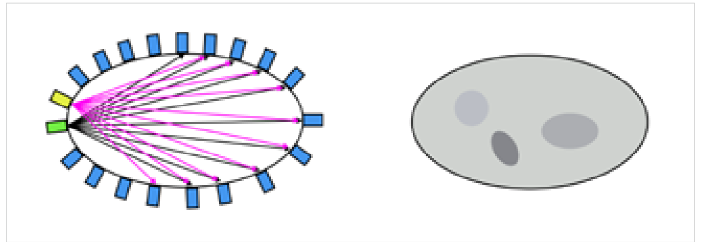


Figure 17: Principle of ultrasound tomography: probe positioning (left), regions with different speed of sound (grey scaled) (right) © Peter Weber, Fraunhofer IBMT

Doing ultrasound tomography several probes are positioned around the object in a cross-section. One probe is used as transmitter (green), and most of the others are used as receiver (black arrows). After all receivers have received the transmitted pulse, the next transmitter (yellow) emits a pulse and again, most of the others are working as receiver (pink arrows). This cycle is repeated, until every probe has been working as a transmitter. If the distance between the transmitting and the receiving probe is known, the speed of sound along the travelling path between both probes can be calculated from the travelling time, which is measured. If the speed of sound in the cross section is not constant, what is the case in most sculptures made of marble or stone due to weathering or other reasons, a map of the speed of sound can be calculated (see Figure 17, right side).

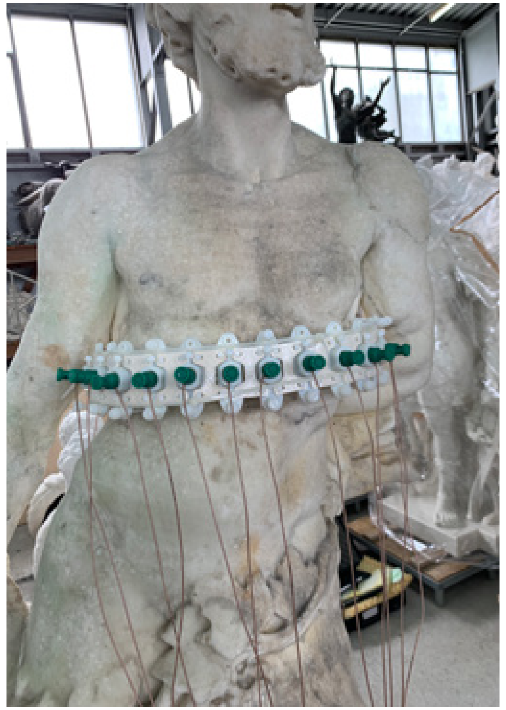


Figure 18: Ultrasound Tomography System: classical method with two probes (left), new approach using many elements along a belt (right)
© Peter Weber, Fraunhofer IBMT

In the classical approach, only two probes are used so that the position of the transmitter stays constant during one cycle and the position of the receiver changes. Because in most cases this has to be done for all cycles, it takes up to several hours until one cross-section is measured. In several projects including FALKE I a special ultrasound tomography system has been developed, which is shown in Figure 18.

This new system works with a flexible belt carrying up to 32 probes, which can be wrapped around the object to be scanned (see Figure 18, right side). The system needs no liquid coupling, as it is necessary for medical diagnosis. I.e. the surface of the object is not affected by the measurement.

The position of the probes on the surface of the object are detected automatically by a wireless tracking system. The cumbersome and time-intensive detection with a gripping circle is no longer necessary. With the new tomographic system, the time to scan one cross section of an object is reduced from hours to a few minutes.

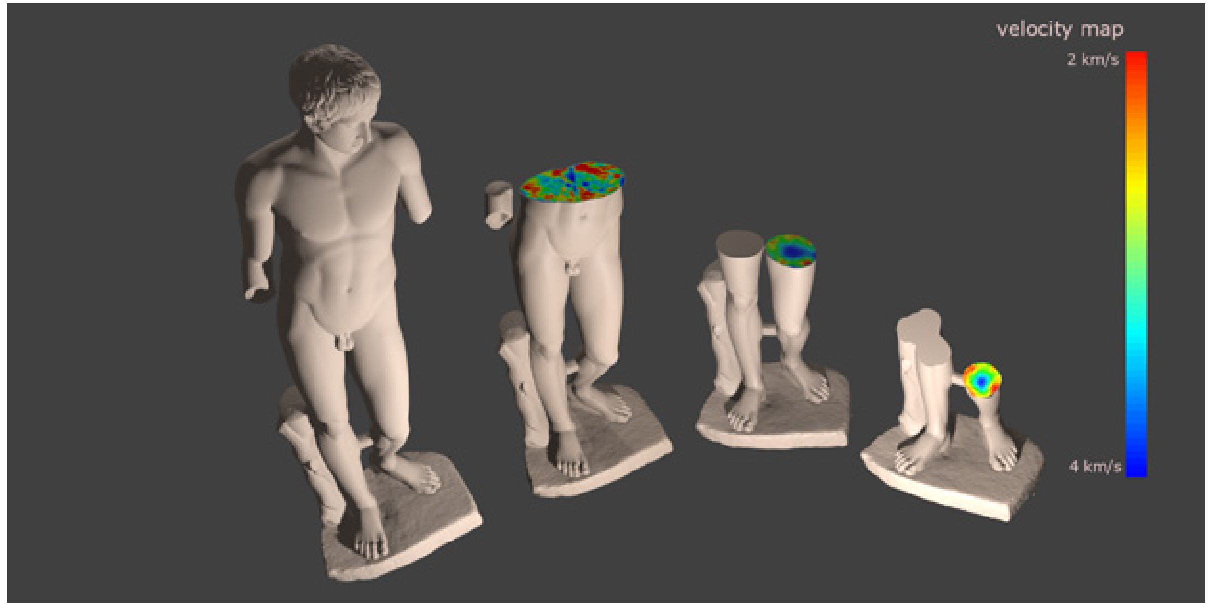


Figure 19: Ultrasound tomograms from different cross sections of the “Dresdner Knabe” © Peter Weber, Fraunhofer IBMT

Figure 19 shows the color maps of three cross-sections scanned at the “Dresdner Knabe”. The mapping is part of the fusion process, which is described in another chapter of this book. The interactive 3D model of the sculpture was scanned using structured light and photogrammetry. As mentioned before the colors represent values for the speed of sound. For a clearer representation in Figure 19 the contrast of the colors was increased, usually the maps are smoother. Using reference measurements of known samples of the same material enables a “diagnosis”, e.g. of the weathering situation inside the sculpture. Internal structures like reinforcement and damages (cracks) can be detected by the method of ultrasound tomography.

4.2 X-ray

Theobald Fuchs (Fraunhofer EZRT)

The practical use of 3-dimensional X-ray images is manifold. Besides the detection of hidden defects or damage the volume data can be used to derive geometrically exact models of the objects under investigation. These digital representations serve as a basis of a digital twin (besides data generated by other methods) as well as of physical reproductions of historical pieces of art or technology by 3D printing. Physical copies cannot replace the originals, but have several applications in the field of public exhibitions, restoration/repair and research, in particular when it comes to collections of natural history or early technology. As an example, a precious clockwork from the 18th century can be rebuilt by 3D printing to study the mechanics, the 3D data sets of similar clockworks spread in museums and collections all around the world can be compared and examined online, and re-scaled cheap copies made of plastic can be promoted as souvenirs or pedagogical toys etc. In the case of the huge collections of biological or geological samples, millions of objects will become accessible to a broader community of researchers or interested public via 3D digitization for the first time at all.

4.3 Terahertz

Fabian Friederich, Maris Bauer (Fraunhofer ITWM)

As described in the respective paragraph 3.4, terahertz imaging can be employed as a complementary NDT technique besides well-known optical, ultrasound, and X-ray techniques. In particular because of its non-contact and non-hazardous nature, terahertz NDT techniques can be safely applied on highly sensitive and extremely valuable – and often unique – objects of artwork and cultural heritage. We demonstrate here some exemplary application of 3D volumetric terahertz FMCW imaging to various materials and to actual artwork. The typical lateral and depth resolutions on the order of a few millimeters in the terahertz images can reveal interesting hidden features, inner structures, and internal defects in such objects.

Example 1: Investigations of some typical materials

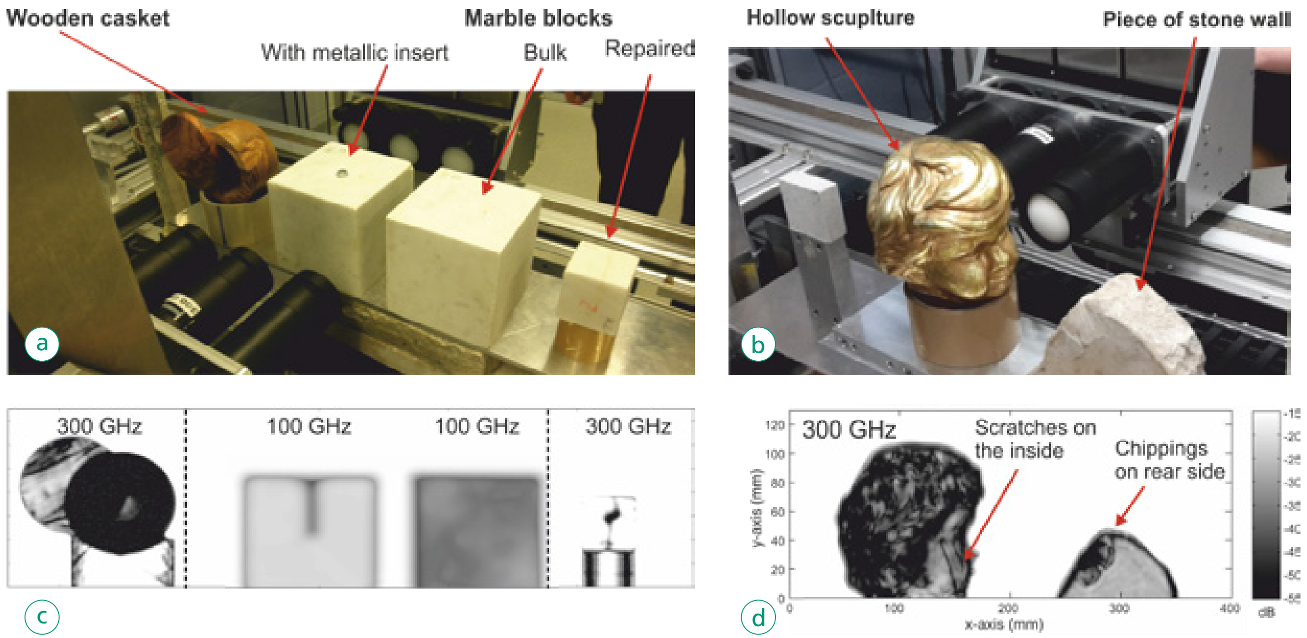


Figure 20: Terahertz measurements on some typical artwork materials © Fraunhofer ITWM

Figure 20 shows investigations on a set of typical materials often found in cultural heritage objects, namely wood, marble, stone and plaster. The photographs in Figure 20a and b on the top show the terahertz imaging scenario in transmission geometry, where – in contrast to the transceiver from Figure 10a in paragraph 3.4 working in reflection geometry – the terahertz FMCW source and receiver are laid out as separate components placed in front and behind the objects to be investigated. With this setup, the transmission of the terahertz waves through the object can be recorded. Figure 20c and d show terahertz images of the investigated objects acquired with FMCW systems working at 100 and 300 GHz center frequency, respectively. The images reveal the volumetric imaging capability of the terahertz FMCW technique, where for each image, a relevant depth layer inside the objects is shown. On the left of Figure 20c, the wood grain of the casket lid is revealed. In the two images at the center, the inside of the two marble blocks is displayed to show the penetration capability of terahertz radiation through the material. The hidden metallic inset in the block on the left is clearly revealed. Finally, the marble block on the right was split in two pieces and then repaired by joining the pieces together again. In the terahertz image at 300 GHz, the crack elongating through the entire block as well as an additional void can be recognized. The terahertz image of the hollow plaster putto in Figure 20d shows that the radiation can also penetrate objects with a certain curvature of the surface. A scratch on the inside of the putto's cheek is revealed which could not be anticipated from the outside. On the piece of stone wall, a chipping on the rear side can be identified in the terahertz images.

Example 2: Enhancing relief contrast by terahertz imaging (digital twin)

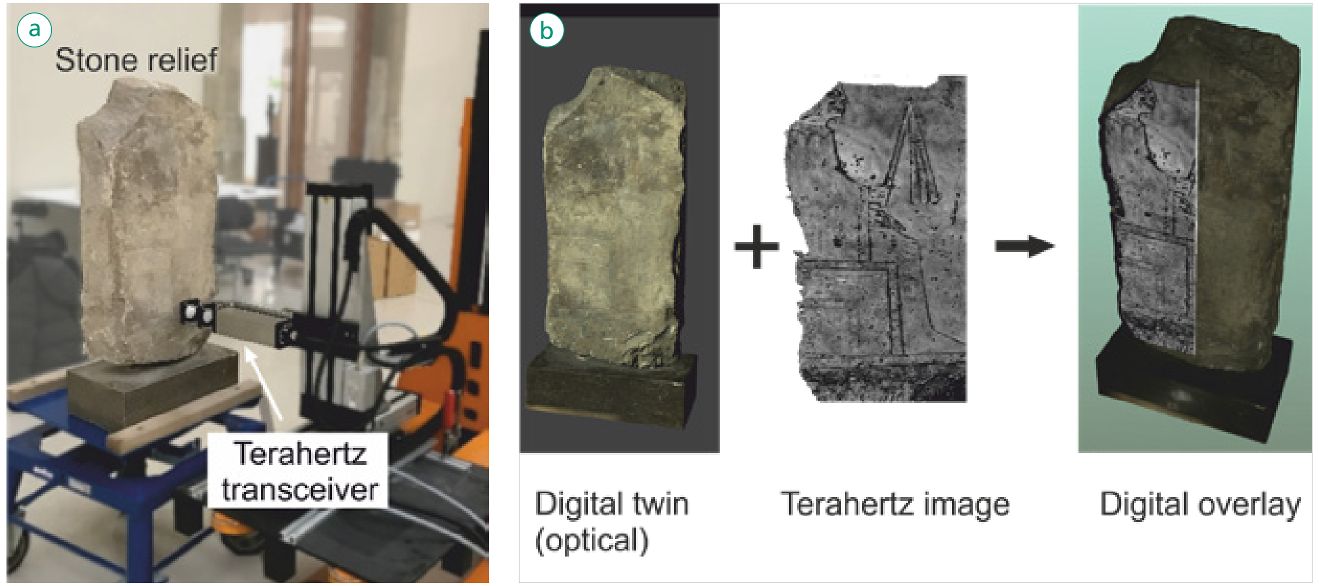


Figure 21: Terahertz FMCW raster scan of Egyptian stone relief (a), digital twin (high-res optical 3D model) overlayed with terahertz image for enhanced surface contrast (b)

Terahertz FMCW reflection measurements – due to the accessibility of depth information – can reveal surface relief information, which might otherwise be obscured to optical camera technologies due to a lack of contrast in the visible range of the EM spectrum. With proper evaluation techniques of the signal's phase information, even sub-wavelength range resolution can be achieved (Ayhan et al., 2011).

Figure 21 a shows terahertz FMCW measurements being performed on an Egyptian stone relief during a measurement campaign at the museum Staatliche Kunstsammlungen Dresden (SKD) in Germany. The terahertz transceiver was raster-scanned over the surface area of the stone wall to generate the full 2D images. Figure 21b on the left shows a digital twin of the stone with the relief barely visible in the optical high-res model. On the other hand, the recorded terahertz surface image in the middle shows the relief clearly visible with high contrast. On the right, the terahertz data is digitally overlayed over the relief's optical model, showing that measurement information from the terahertz spectral range can be included to enhance the information of digital twins of artwork objects.

Example 3: Terahertz transmission through marble statue

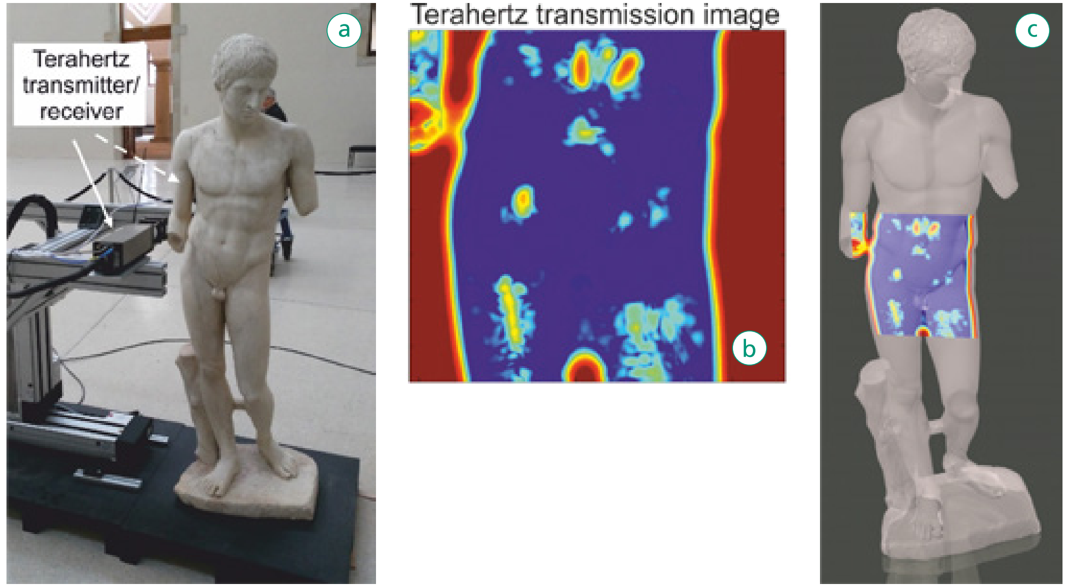


Figure 22: Example, Dresdner Knabe THZ Transmission

The marble statue "Dresdner Knabe" from SKD in Dresden, Germany, was investigated in terahertz transmission measurements alongside the ultrasound investigations described in paragraph 4.1.

Figure 22a shows the mechanical raster-scanning measurement setup with the terahertz transmitter in front and the receiver (not visible) behind the statue.
Figure 22b shows the respective terahertz image recorded with an FMCW system at 100 GHz center frequency, and
Figure 22c shows again an overlay of the terahertz data over a digital 3D model of the marble statue. It should be noted that blue areas in the transmission correspond to low and red areas to high transmission values. For strongly curved surfaces, the interpretation of such data can be quite complicated as both radiation scattering and absorption in the material can in principle lead to signal attenuation. In such cases, complementary information on the object, e.g., from the parallel ultrasound investigations, can be used to distinguish between geometrical and material-related influences on the terahertz transmission images.

Example 4: Investigations of Leonardo's The Last Supper

Terahertz FMCW measurements can be employed as a contact-free, non-destructive measurement technique when structural investigations on highly sensitive, unique objects of artwork are to be performed. One such example of unique artwork is without a doubt Leonardo da Vinci's famous mural painting "The Last Supper" in Milan (ital. "L'Ultima Cena", Museo del Cenacolo Vinciano, Milan, Italy). The painting is of particular interest for structural investigations due to two reasons.

First, the wall with the painting was impacted in World War II by bombings of the city of Milan. Although the painting itself could be protected, it is suspected that its supporting wall took heavy damage during the air raids. Here, terahertz technology can help to reveal sub-surface cracks and structural damages of the wall (Bauer et al., 2020; 2022). Second, Leonardo created his masterpiece as a mural painting on a dried mortar-based top preparation layer in contrast to the buon fresco technique common at the time (Basile & Marabelli, 2008). Terahertz depth profiles can help identify the structure of preparation layers beneath the visible wall painting (Fukunaga et al., 2020).

Figure 23 shows photographs and terahertz data from a measurement campaign at Milan for non-destructive investigations on "The Last Supper". Figure 23a and b show a mobile terahertz FMCW raster-scanning system in front of the painting. The system covers an area of roughly 20x30 cm² for a single terahertz image and was designed to work at 100 GHz center frequency for this campaign. In parallel, terahertz TDS measurements were performed with another system in parallel (Fukunaga et al., 2020).

Figure 23: Example, crack-detection Leonardo da Vinci "The Last Supper", reproduced after Bauer et al. (2022)

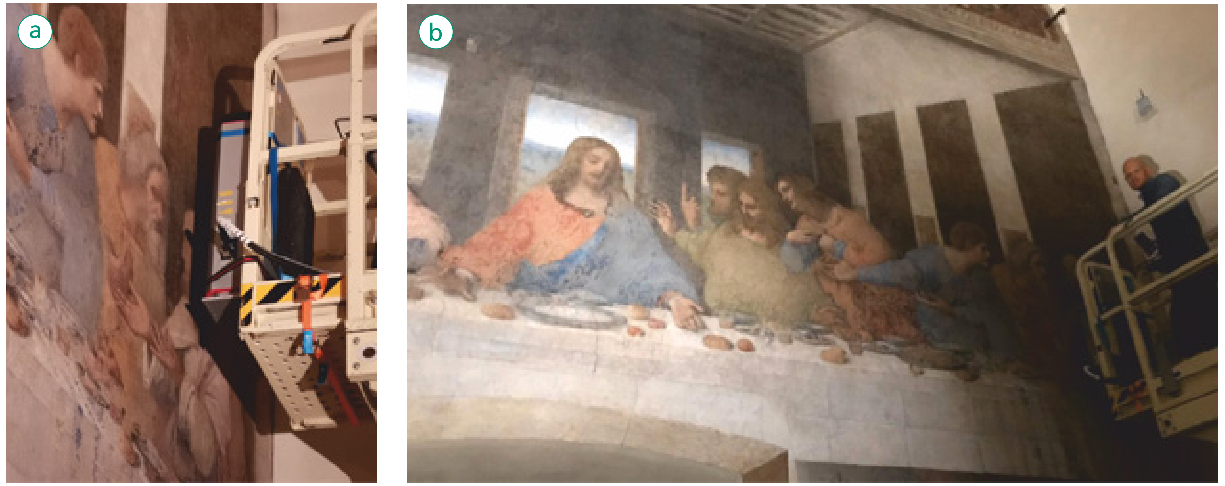
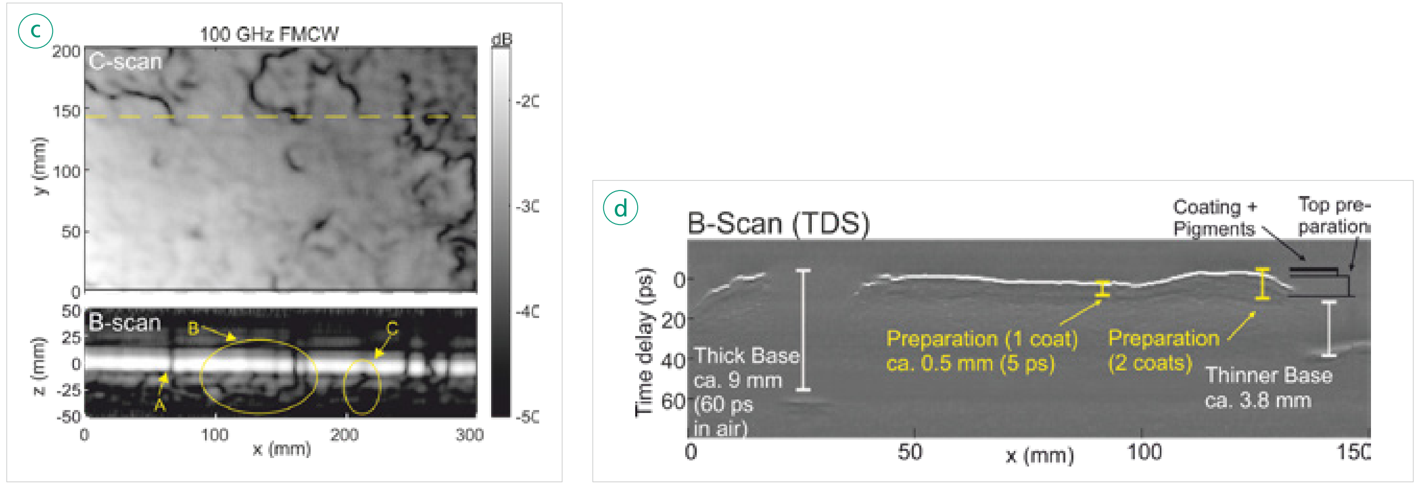


Figure 23c shows a terahertz image of an area of the painting, where several surface defects can be recognized in the C-scan. The B-scan (depth line scan) below reveals that some of those defects extend straight down to the deeper preparation layers (label A). Some of the crackings, however, seem to extend in different directions below the top layer (label B) or are solely present in the deeper layers, not visible from the surface at all (label C).

Figure 23d shows a B-scan (line scan) obtained from the terahertz TDS measurements, the vertical axis representing time delay of the measured terahertz pulses or distance/layer thickness, respectively. From the individual reflection signals in the image, the thickness of a thin preparation layer (ca. 0.5 to 1 mm thickness) can be identified on top of the thicker base layer. Here, terahertz information can substantiate the previous findings (Basile & Marabelli, 2008) that the painting was indeed painted on a thin top preparation layer in a fresco secco technique.



4.4 Microscopy

Erich Jelen (Fraunhofer UMSICHT)

Measurement campaigns: Microscopy goes mobile

Within the framework of Fraunhofer projects FALKE I and II, measurement campaigns were carried out on selected objects of the Staatliche Kunstsammlungen Dresden (State Art Collections). As examples, two objects were selected from the Skulpturensammlung Dresden (sculpture collection). As described above, microscopy is a good tool for the detection of disadvantages or failures of museum objects. Therefore two different sensors were used: a digital microscope and a confocal microscope.

In two campaigns at the Skulpturensammlung, investigations were done on the “Dresdner Knabe” and an Egyptian plank. In the first campaign, previously unsurveyed parts of the objects were scanned, and using a handheld microscope, cracks at the foot of the Dresdner Knabe were detected.

With the mobile digital microscope, the surface of the plank was scanned to look for cracks and bubbles because of water impact.

Figure 24: Small handheld digital microscope and detected cracks
© Erich Jelen, Fraunhofer UMSICHT

Figure 25: Mobile digital microscope and detected spalling
© Erich Jelen, Fraunhofer UMSICHT

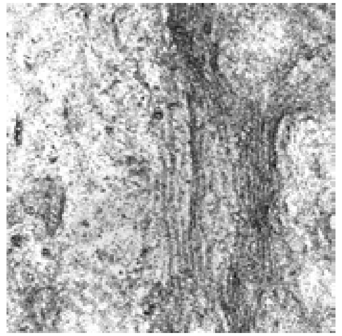
Coincidentally, layers of paint were detected, which were not recognized before.

In the second campaign, the mobile confocal microscope was used to measure the topography at selected points of the Egyptian plank.

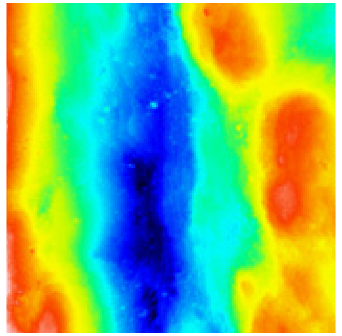
Figure 26: Confocal sensor © Erich Jelen, Fraunhofer UMSICHT

The following picture shows an example for the measurement and analysis.

Photo of selected point Egyptian plank

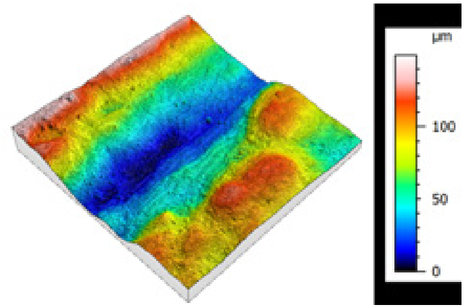


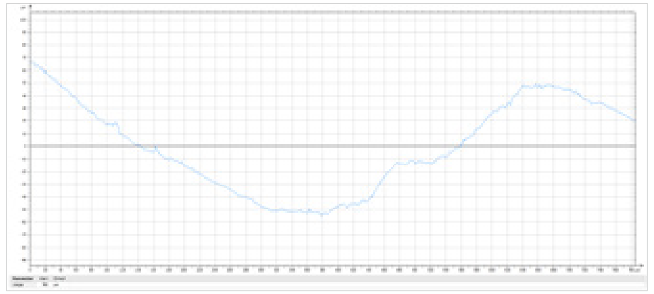
Reflection data



Height data

3D Topography





Profile

Figure 27: Measurement and analysis © Erich Jelen, Fraunhofer UMSICHT

The photo of the selected point was done with a digital camera to document the point. Within the measurement, the reflection data and the height data were determined. For a better illustration, the height data are shown in rainbow colors and each color stands for a height data. From the image stack of the height data the 3D topography was calculated. To measure the depth of the gutter a profile analysis was done. The analysis software has more evaluation tools, e.g. to calculate the roughness, which gives for example an indication of incipient corrosion, surface treatment or water ingress.

5. VISUALIZATION FOR CULTURAL HERITAGE

Sylvain Renault, Oliver Schreer (Fraunhofer HHI)

5.1 Introduction

"Visualization is any technique for creating images, diagrams, or animations to communicate a message." [VISUALIZATION, Wikipedia]

Nowadays, many different techniques are used to access visual information ranging from stationary devices like personal computers to mobile devices such as smartphones and tablets. In the context of cultural heritage, attractive and actual visual content is offered to the general public, visitors in museums, memorial sites and cultural heritage sites, as well as to the researcher community. Novel imagery and video services are continuously created and offered on-demand for free or as fee-based. In the last years, users expected to access desired information anytime and anywhere, in particular with internet ready devices and modern apps.

To preserve the cultural heritage (CH) for future generations, a huge amount of digitized information on cultural sites, buildings and cultural heritage artefacts is created by technologies as presented before in paragraph 3 Scan Methods. Current capture devices offer higher scan resolution with increased accuracy and therefore lead to an increasing amount of data in the digital world. The presentation of such data encloses not only the visualization of photos, videos and rendering of 3D sceneries and models (e.g. digital twins, see paragraph 2) but also the presentation of other documents such as explanatory text, annotation labels and historic and scientific manuscripts. Animations and interactive applications allow to present the relevant information to the user in a more understandable way.

Cultural heritage data representing the "things" to be visualized in the digital world are stored in assets. Assets contain any kind of data, ranging from still images, videos, 3D data, animations or even link to other assets. They are stored in dedicated databases, managed by museums, institutions or companies. Cloud services make them accessible locally or via the internet (see chapter 1, The FALKE Knowledge Base). For the asset management, conventional relational databases such as SQL are used since a very long period (1980 and earlier) [SQL], but non-relational database such as NoSQL are often easier to be included in the development [NOSQL]. Open-source solutions like MongoDB and MariaDB are preferred nowadays and allow for creation of lightweight, licence-free applications [MONGODB][MARIADB]. For CH use cases, some Fraunhofer institutes propose modern solutions with web interfaces – accessible from anywhere – as the Cultural Heritage Repository platform written for the web language JavaScript [CHR] or the SPARQL based platform WebGenesis that include the modelling of complex ontologies [WEBGENESIS]. In the European context, the Europeana project started almost 15 years ago. Its mission is to share and promote European cultural heritage to be used and enjoyed by everyone for education, research and entertainment [EUROPEANA].

The digital transformation in the CH sector will lead to an increasing amount of data that need to be stored on servers and accessed easily. Hence, the reduction of memory consumption and transport payload is a key. In the context of 3D data and related interactive applications, compression algorithms such as glTF [GLTF] are used. Content creators and developers use a variety of editors and tools to generate digitized CH assets and applications. In order to integrate the CH assets in the development pipeline, assets are collected in media packages or libraries that are organized by categories, epochs, or countries. Through these media packages, CH assets are made accessible to different visualization platforms such as 3D editors, render engines and game engines, no matter if they are required in the design phase, e.g., for authoring, storyboard or mock-up development, or at runtime, when the user runs the app.

Figure 28: High-resolution autostereoscopic displays showing CH assets in 3D (left, prototype © Fraunhofer HHI), VR Experience "Ernst Grube – The Legacy" (middle © Fraunhofer HHI), Mobile AR application CHESS (right © Fraunhofer IGD))

5.2 Technologies for CH visualization

"Computer-generated Imagery is the application of computer graphics to create or contribute to images in art, printed media, video games, simulators, computer animation and VFX in films, television programs, shorts, commercials, and videos" [CGI, Wikipedia].

To be attractive to the consumers the visualization of cultural heritage CGI assets, as created in the FALKE project, requires modern and performant render engines and display technologies. Twenty years ago, conventional displays such as desktop monitors or TVs were extended being capable to present 3D content by using special 3D-glasses or glasses-free. For this case, the user doesn't need to wear any glasses: The autostereoscopic presents the left and right views, perspective correct, at the same time (see Figure 28, left). In the last ten years, computing power increased, and form factor of the devices became smaller. Hence, a new rise of Virtual and Augmented Reality happened, while a number of new devices reached the mass market. This is noticed for head-mounted-displays (HMD, wireless or not) and powerful smartphones and tablets with special 3D chipsets and high-resolution cameras. Those mobile devices can be used in-door (at home, in museums) and outdoor, in the city and on the street. In FALKE, several Fraunhofer institutes produced CH applications for VR (see Figure 28, middle), for AR with tablets (see Figure 28, right) and also stereo and auto-stereoscopic display and kiosk systems with gesture control (3D-BookExplorer and 3D-Kiosk, see Figure 29).

As a result of this development, cultural heritage content can now be presented with modern interactive eXtended Reality (XR) technologies. These technologies offer improved user involvement in the historical environment, no matter if it's a reconstructed virtual one (VR) or a virtually augmented location (AR).

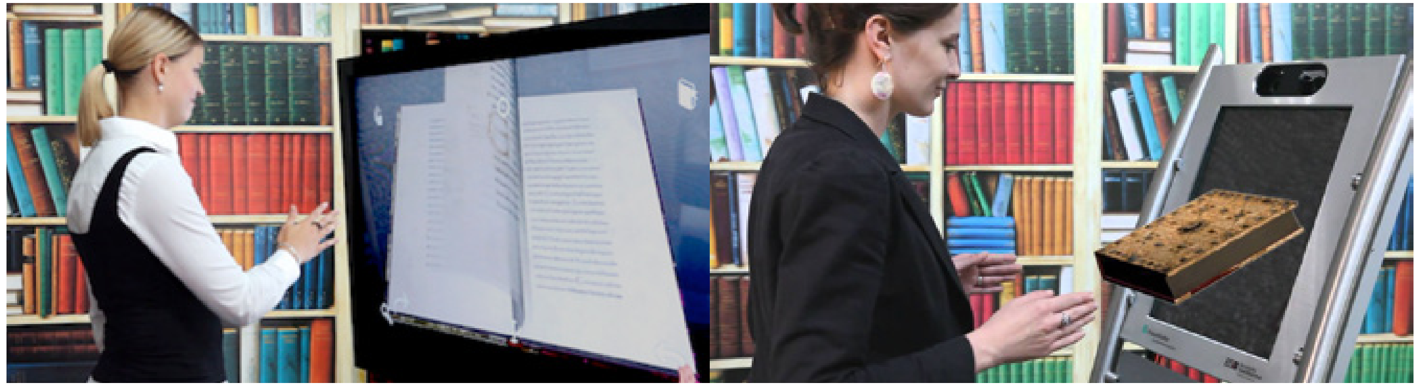


Figure 29: Book-Explorer (left), 3D-Autostereoscopic Kiosk – all with user tracking and gesture-control (right, Fraunhofer HHI)

But what are the differences between VR, AR and XR?

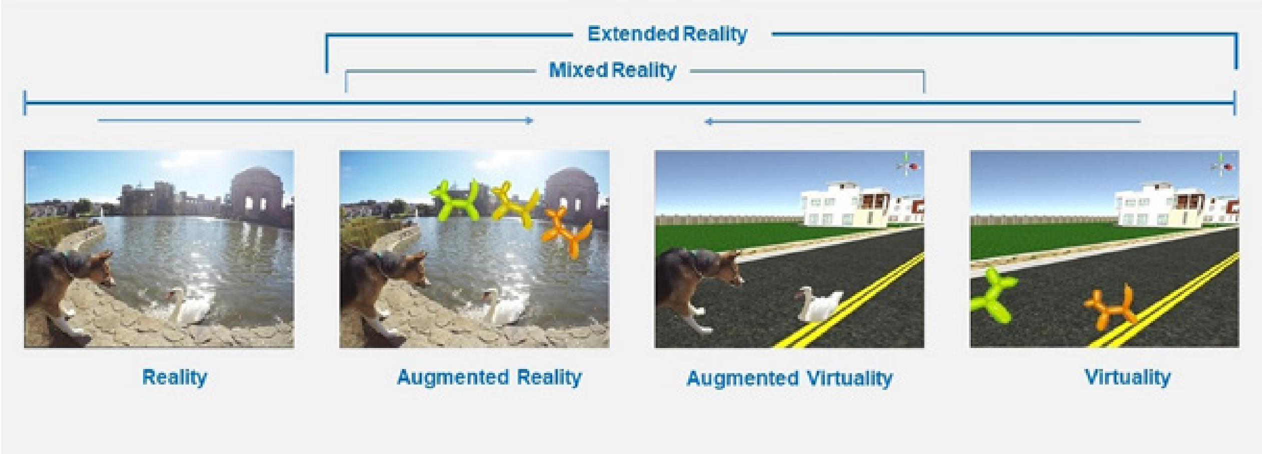
The H2020 project XR4ALL [XR4ALL] presented a terminology based on Paul Milgrams well-known Reality-Virtuality Continuum defined in 1994 (Milgram et al., 1994). It explains the transition between reality on the one hand, and a complete digital or computer-generated environment on the other hand. However, from a technology point of view, a new umbrella term has been introduced, named eXtended Reality (XR). It is the umbrella term used for Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), as well as all future realities such technologies might bring. Hence, XR covers the full spectrum of real and virtual environments.

Figure 31: Virtual video conferencing © Fraunhofer HHI

Starting from left-to-right (see Figure 30), Augmented Reality (AR) consists in augmenting the perception of the real environment with virtual elements by mixing in real-time spatially registered digital content with the real world. Pokémon Go and Snapchat filters are commonplace examples of this kind of technology used with smartphones or tablets. AR is also widely used in the industry sector, where workers can wear AR glasses to get support during maintenance, or for training.

Augmented Virtuality (AV) consists in augmenting the perception of a virtual environment with real elements. These elements of the real world are generally captured in real-time and injected into the virtual environment. The capture of the user's body that is injected into the virtual environment is a well-known example of AV aimed at improving the feeling of embodiment. A well-known scenario is virtual video conferencing, where participants from different locations take place in a common virtual meeting room (see Figure 31).

Figure 30: Extended reality scheme © Courtesy H2020 XR4ALL



Virtual Reality (VR) applications use headsets to fully immerse users in a computer-simulated reality. These headsets generate realistic images and sounds, engaging two senses to create an interactive virtual world.

Mixed Reality (MR) includes both AR and AV. It blends real and virtual worlds to create complex environments, where physical and digital elements can interact in real-time. It is defined as a continuum between the real and the virtual environments but excludes both of them.

With the raise of 3D portable devices for the mass market, 3D software companies took the challenge to propose new kind of development tools, compatible to most common 3D output devices and common operating platforms such as Windows, Android, iOS and Sony PlayStation 5.

How to develop amazing XR applications today?

For developing and programming amazing XR applications, developers have to select the appropriate tools for creating and editing 3D assets and for programming the application logic including 2D, 3D and VR user interfaces. The toolchain should be simple and coherent in transferring and importing data and handling multiple file formats. For the creation and modification of 3D assets, conventional 3D editing, and animation software is available on the market. Some of them are from the industrial domain, e.g. CAD/CAM [AUTOCAD], [CATIA], [PTC]. For more scientific datasets a freeware solution can be considered, e.g. MeshLab [MESHLAB] – especially developed for the needs of the ICT/Cultural Heritage domain (Cignoni et al., 2008) and for multimedia, entertainment and gaming (as well as for movie industry) Maya, Blender, 3ds Max, Houdini, Cinema4D are good candidates. Recently, Blender became more and more popular because it's free and has a very active community.

The second choice while developing an XR app is the choice of the real-time engine: the engine running the application on the XR device. Unity [UNITY] and the Unreal Engine [UNREAL] are today the most relevant editors for the development of interactive and gaming apps as they propose plenty of modules, assets and plug-ins to help designers and programmers. They are usually called Game Engine. Several open source game engines also exist e.g. the Godot [GODOT] or Open3D engines [O3DE]. Some other engines are dedicated to industrial use cases such as Instant Reality from Fraunhofer IGD [INSTANTREALITY] supporting other industry related file formats and following a different real-time and interaction concept.

The main advantage of Game Engine editors is their capability to design complex interactive VR/AR scenarios for all current head-mounted-displays and mobile devices. All editors allow to define complex user interactions (UX) for touchscreen (for smartphone or tablet) or contactless via gesture (for HMD with on-board cameras). Towards standardization, the OpenXR 3D group of Khronos [OPENXR] works on an open solution for eXtended Reality authoring tools and drivers to facilitate the integration of XR in different devices. The editors have usually an integrated compiler and can deploy the final application or the game directly on a device, or on a store as provided by many companies.

5.3 Examples for interactive CH applications

During the course of the FALKE project, several interactive applications and demonstrators have been developed in order to showcase the potential of this technology and the benefits for the CH sector to make CH artefacts more accessible.

Solution for a 3D Kiosk System

The first system implemented in the project is a 3D kiosk system that allows to visualize CH data in 3D. This stationary system is based on the 3D workbench concept [WORKBENCH3D]. The user (e.g. visitor of a museum) has access to digitized content from the FALKE Knowledge Base via a web-based interface. The system can be placed anywhere in a museum (entries, lounge, exhibit rooms) and can be used by experts as well as by lays, no matter if young, adult or aged people. The visualization in 3D allows a better understanding of the digital content and augments the interest of any user: it looks magical and values the realism and quality of the rendering of the 3D objects. The examples in Figure 32 (left) show the statue “Dresdner Knabe” from the German museum Staatliche Kunstsammlungen Dresden (SKD).

The 3D-Web Workbench is easy-to-use and has a finger- and gesture-controlled display. Three base technologies support system innovation and user-friendliness:

- a touchscreen 2D display to control the content,
- a 3D autostereoscopic visualization display, and
- a Web 2.0 compatible software with stereo-rendering and modern user interface.

The control display has touchscreen functionalities for (1) the selection of CH assets via the left-hand side menu, (2) the rotation of the 3D model in the preview window and (3) for the access of historical or scientific information and explanations about the exhibit/artefact (e.g. a 3D rendering, see Figure 32, middle). The top display is an autostereoscopic display allowing the user to get a 3D view of the artefact without the need of dedicated 3D glasses (Figure 32, right). It is oriented frontal to the user’s and presents a natural 3D image. The system was extended with a gesture recognition camera-based device. The interaction volume is positioned in front of the screen, where the object appears. It is a natural way to interact with 3D computer generated graphical assets.

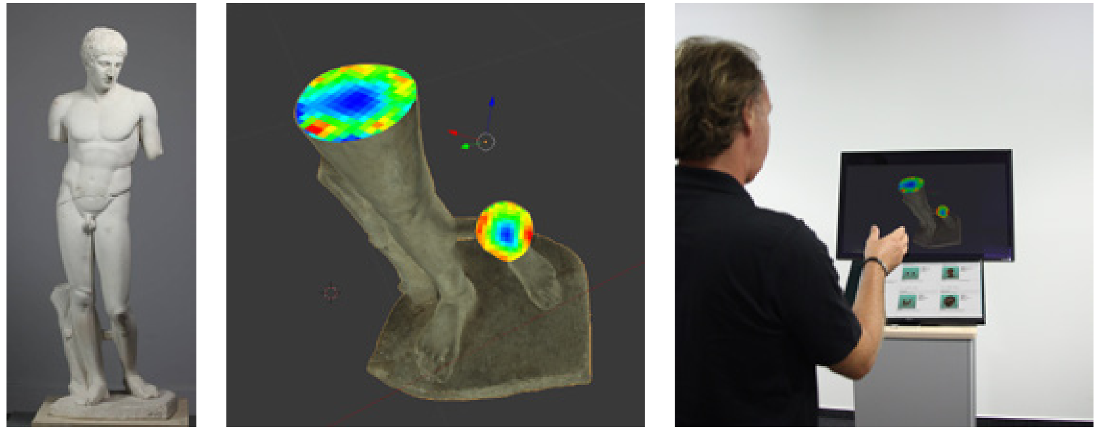


Figure 32:
Statue of “Dresdner Knabe”
© SKD, Dresden (left),
Rendering of 3D scan with ultra-sound maps, cutting the geometry model
© Fraunhofer IBMT (middle),
touchless 3D-Info-Point
© Fraunhofer HHI (right)

Figure 33:
Web-interface from the 3D-Web Workbench with CH asset selection area from the FALKE Knowledge Base (left), model view area (middle) and information area (right)
© Fraunhofer HHI

How does the web interface work?

The web page (see Figure 33) is programmed via the HTML2.0 internet language, the programming language JavaScript and a compatible 3D library X3DOM from the Fraunhofer IGD [X3DOM]. The data are retrieved from the FALKE Knowledge Base (see chapter 1) and presented in a menu. After selecting an asset, the user gets a preview of it and some information via an embedded second webpage, scrollable via the touchscreen. The geometry model of the asset is presented at the same time on the 3D display on the top.

...and how does the 3D system work?

The special 3D display converts a side-by-side input rendering (left and right perspectives of a 3D scene) in a multi-view picture. These two images are rendered using X3DOM in a special graphic program mode (shader), in the web-page top screen. The shader code controls directly the GPU of the graphic adapter. The display produces then a combined left-right image that is viewed by the user through a special optical lens (similar as in Figure 28, left: the unsharp image will be sharp when the user is located in front of the screen). The user’s head is continuously tracked by the system to adjust the combined image (real-time adaptation).

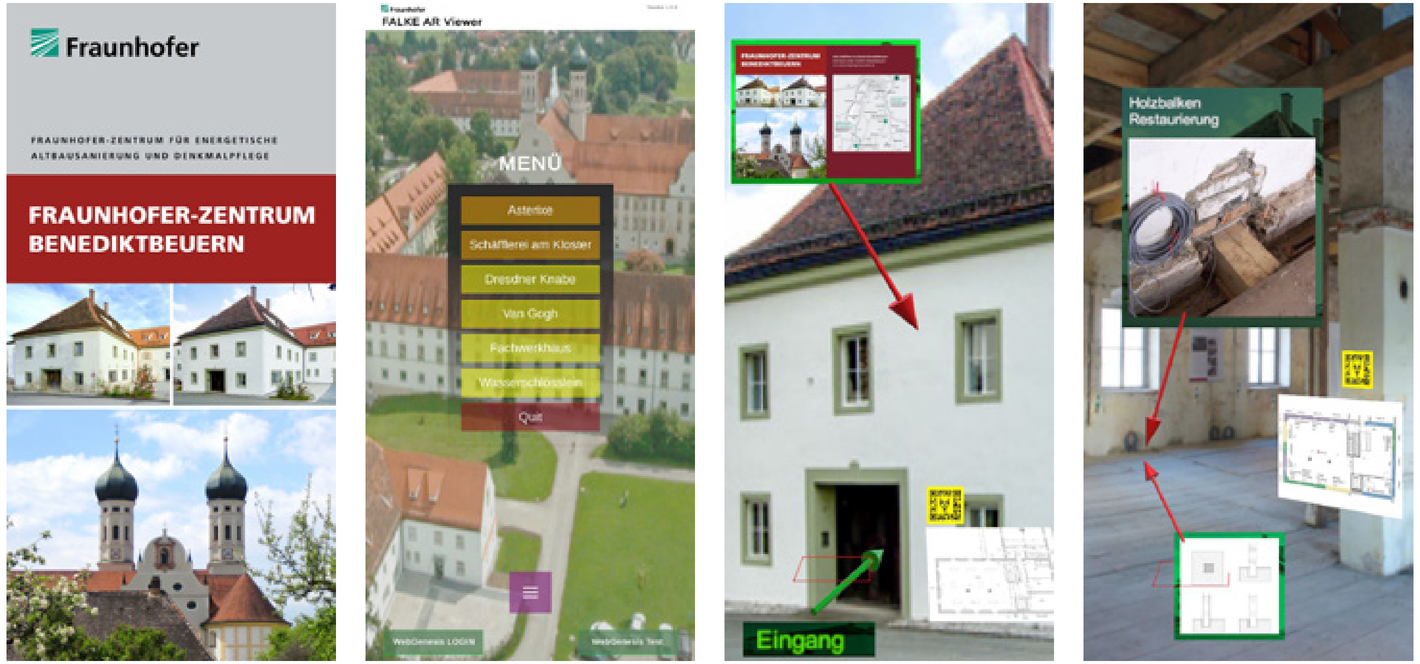
For the interaction, the user moves the hand where the object appears in space, in front of the display. It works completely touchless (see Figure 32, right). Moving the hand to the top/bottom or left/right is used to rotate the asset. The size of the model can be controlled by the touchscreen system (bottom display).

Solution for an AR System

The second implementation within the FALKE project is the "AR-Info-Point". It is a mobile system using Augmented Reality to visualize additional information in a real environment where the user is currently walking around (see explanation of AR technologies in paragraph 5.2). The AR application is suitable for museums or exhibitions, where selected exhibits can be augmented with digital assets and diverse media datasets describing the object.

Different functionalities are prototyped in the AR application in FALKE. They were established in collaboration with several Fraunhofer institutes, which produced graphical CH datasets, to be visualized in AR. The examples in the figures below show the use case "Kloster Benediktbeuern, Alte Schäfflerei" (the Monastery of Benediktbeuern, Old Coopery, see Figure 34, left), under the direction of the Fraunhofer IBP. In this museum, all different AR scenarios are presented to the visitors in one exhibition location [BENEDIKTBEUERN]. At the pre-defined AR marked location, the user has to activate the AR compatible device and select the desired FALKE app (see Figure 34, middle left). While looking at a region of interest (ROI), the app receives the information from the FALKE Knowledge Base. The information appears in the room as an image overlay and looks like floating in the air.
A reference between the floating objects and the real point of interest (POI) is visualized by drawing virtual arrows (see Figure 34, middle right and right).

Figure 34: The museum Monastery of Benediktbeuern (left © Fraunhofer IBP), AR Menu with the various FALKE apps (middle left), entry point oriented using the marker and GPS sensor (middle right), POI in the museum showing some CH assets (right © Fraunhofer HHI)



Today, two kinds of AR devices exist on the market: (1) AR with special see-trough glasses, an expensive technology, and (2) AR on mobile devices (smartphones and tablets) supporting a camera-based mix of the real environment with the virtual content. The latter offers wide-spread availability and is used within this project.

The FALKE AR solution allows people to (1) walk freely outdoor e.g. in the city, in streets, in parks and receive virtual CH content on the way (out-door scenario, GPS based) and (2) walk inside a building, in rooms or floors, and receive the assets in predefined locations (marked by an AR tag, in-door scenario). By creating a scenario, the developer has to decide which system is suitable.

What are the requirements given by an AR app?

- The device needs to be compatible to AR tracking. For this, lists are published by Android and Apple to look for compatible devices.
- The device should have a powerful CPU and a good graphic processor.
- For outdoor usage:
  - The device requires good GPS connectivity.
  - The device requires a good functioning on-board compass.
- For outdoor and indoor usage: AR marker must be clearly visible to be recognized by the app.

Fraunhofer HHI developed the AR-Info-Point with the game engine Unity, a modern development editor (IDE) used for programming games, but also entertainment and industrial real-time software [UNITY]. Based on the AR development framework at Fraunhofer HHI (programming libraries and components), special authoring modules for the FALKE showcase were added step-by-step into the framework. Some new requests for extra AR functionalities came from the partner institutes rapidly as the potential of AR technology was discovered.

The FALKE framework proposes some solutions to the following topics: (1) the access to the content that will be shown in the AR view (the FALKE Knowledge Base WebGenesis [WEBGENESIS]), (2) the definition of the AR scenario with authoring in Unity, (3) the localization of the user or user's device (in-door and geo positioning) and (4) the presentation of the assets and other information on the screen (3D rendering). A user interface was implemented to allow the navigation between the different use cases (menu, see Figure 34, middle left) and to select 2D and 3D content on the touchscreen of the device. Several AR scenes (one per use case) were developed in separate Unity "level" and can be separately published, so, that all partners may get its own version of the app. For the common use case "Alte Schäfflerei", the assets and components were mixed in one scene, using new ROI/POI locations adapted to the exhibition of the museum. The content proposed by partner institutes is linked to those fixed POI positions in the exhibits or outside the building (outdoor scenarios). The system mock-up with different POIs is depicted in Figure 35, right.

But how should graphic information be placed in the real world?

The framework is based on a special technique to assign real world locations (ROI or POI) to the related digital content: it uses a “trackable and world anchors” component model (for more details, see also [ETSI-ARF]). In the Unity scene, some special objects, so-called place holders, are placed and assigned to an AR marker (a small image, looking like a QR code, see Figure 36, right) or a GPS marker (outdoor scenario, [GEOPOSE]). This marker is then linked to the graphical CH content, loaded at runtime from the FALKE Knowledge Base. One unique AR marker or GPS coordinate is required per exhibit or artefact. The implementation in Unity is based on the AR Foundation programming package available for Android and iOS devices. This allows to develop AR apps for these two major device categories without the need to redefine the whole project.

When using the app, the user needs to scan the AR marker with the device or must be located close to the GPS marked position. Then, the CH assets or augmented information automatically appears in front of the user on the screen. Now, the user can move freely in the room, while the rendered assets remain fixed in space. The marker system can not only be used to present the CH data but also for a simple navigation and also complex guidance through an exhibition as depicted in Figure 35, right. In the mock-up, markers are drawn in yellow and are located at strategic position (e.g. building entries, rooms, exhibits, etc.). For outdoor scenarios, the geo positioning system and the compass orientation of the device is required to get the orientation of the user in space.

Figure 35: The monastery (left) and its system mock-up for the AR authoring and guidance (right © Fraunhofer HHI)

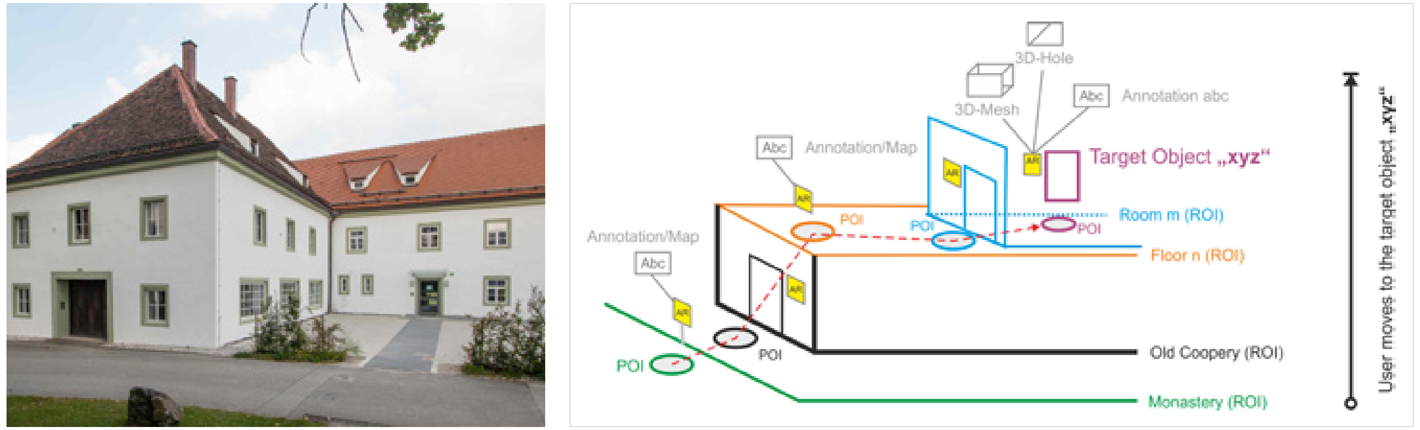


Figure 36: Assets management for the guidance and AR augmentation in the museum (left), special AR Marker for the museum (right) © Fraunhofer HHI, flyer and photos: © Fraunhofer IBP

Which type of assets can be visualized in the AR app?

The database contains ready-to-use AR assets, already imported by the developer or by other authors (institutes, companies…) involved in the definition of the AR scenario (see Figure 36). The author of a scene adds special objects, so-called Unity prefabs, in the scene. A prefab includes programming scripts and can load the content at runtime, from the WebGenesis Knowledge Platform, and assign it to the different POI positions in the room.

A prefab includes also the way how an object should be rendered by the graphics engine. The Unity base system can render any geometric objects and user-interface elements. The universal render pipeline (URP, compatible with modern mobile devices) allows to extend the quality of materials and textures of 3D meshes by applying and programming visual effects (e.g. via the VFX shader graph). So, 3D models are rendered in a real fashion with transparencies, reflexions, mirror and translucent effects, if needed and desired. Materials can be mixed to reach higher realism, up to photo-realism.

A few meaningful graphical AR objects were defined by the experts for the FALKE use cases. Most of them are common, some of them dedicated to FALKE:

- room maps (areal, buildings, floors, rooms): for guidance, to show the visitor where he/she is and to show the direction to take for the next exhibit,
- text windows: to label single parts of an exhibit,
- description window (with a title, a text and photos): to document an exhibit,
- 3D meshes: to show a 3D geometry model, near or onto the real object (render quality should be adjusted by the author from normal to photo realism),
- inside view: to show information inside an object by overlaying its shape with the 3D reconstructed or scanned interior (special for FALKE),
- time-lap view: sequence of assets to show information or 3D models over time, animated or manually selected (special for FALKE).

5.4 Conclusion

The development of both use cases 3D-Web Workbench and AR-Info-Point out of the FALKE project is considered as a proof-of-concept and starting point for further developments. The apps demonstrate the potential of eXtended Reality technologies for the cultural heritage sector. Furthermore, it offers the possibility to all Fraunhofer institutes to showcase their specific technology. A complete framework is now available, which allows quick and easy development of new AR applications.

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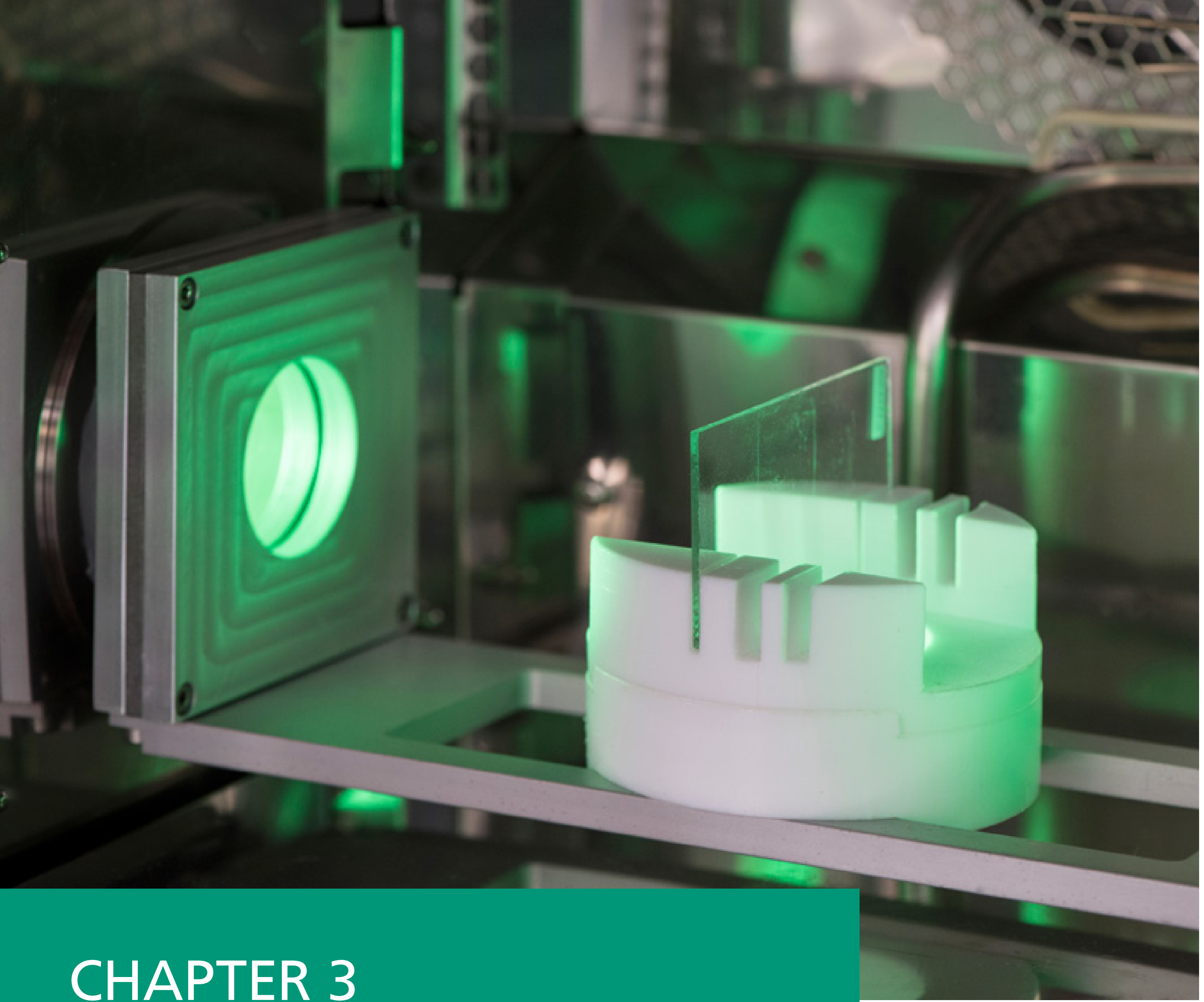

CHAPTER 3

PRESERVATION OF HISTORICAL MATERIALS IN TIMES OF CLIMATE CHANGE

1. PLASTICS IN MUSEUMS

1.1 Adsorption

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Even museum objects made of plastics do not last forever: polymer materials degrade in many ways. For example, the bonds of the molecules can be broken, or the loss of additives can cause cracks in the surface. Characterization of the material and the status of degradation are the first steps in devising a conservation strategy. However, most objects do not only consist of the actual polymer. Additives and fillers are what make it a material, a plastic. Small changes can cause dramatic changes in properties. The objects must therefore be analyzed by various complementary methods to determine the composition and degree of degradation.

Temperature and humidity have a major influence on degradation, especially the variations in temperature and humidity. For certain plastics, it may be important to remove substances produced by decomposition from the surrounding air. Adsorbents are one way to protect objects and surroundings from outgassing. However, their use can also cause damage if it is accompanied by the loss of plasticizers. The aim is therefore to formulate and test alternative adsorbent materials that trap harmful degradation products such as acetic acid and nitrous gases, but do not promote the loss of plasticizers.

Definition

Adsorbents are usually solid substances that are capable of selectively accumulating (adsorbing) certain substances from an adjacent gaseous or liquid phase at their interface.

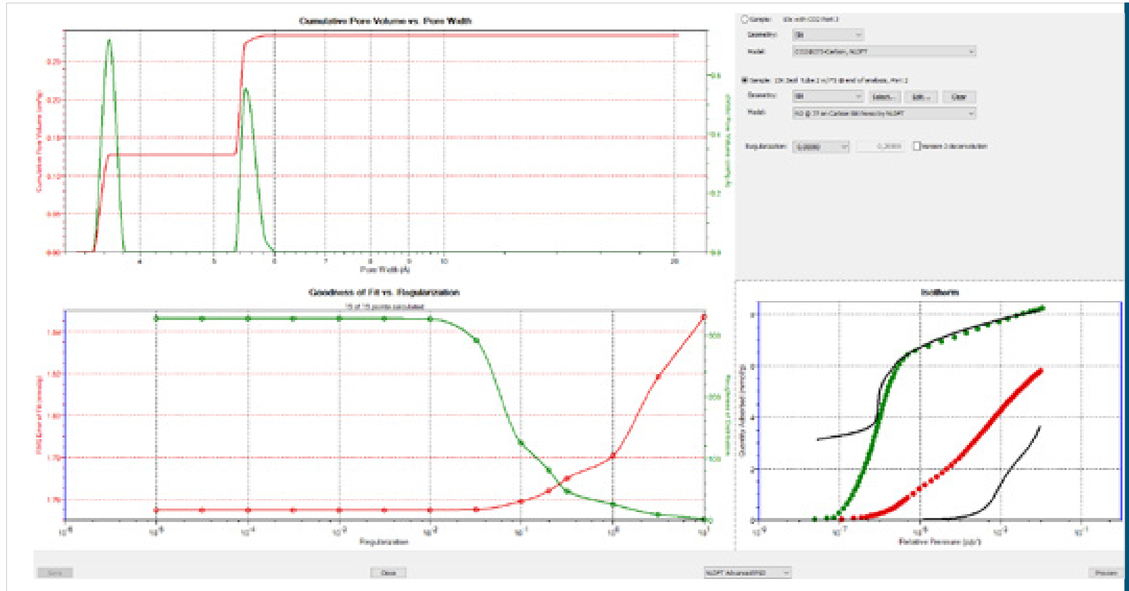
For technical purposes, adsorption can be used if there is sufficient selectivity towards a component from a mixture of substances, which makes it possible to separate a substance from a mixture. In addition, easy and fast desorbability of the adsorbed substance should be possible.

For the technical application of adsorption as a separation process, it is important that adsorption can be carried out in the smallest possible apparatus with small quantities of adsorbent. Therefore, the adsorbents used should have as large a surface area as possible.

The total surface area of finely powdered and porous substances is composed of the outer geometric surface of the substance grains and the so-called inner surface, which is formed by the walls of the pores inside the grains. The inner surface area can be up to 10^6 times larger than the outer geometric surface area. Typical adsorbents are: activated carbon, silica, carbon molecular sieves, alumina, zeolites, and modified types of them.

How to characterize the inner surface?

Of the various methods for determining the total surface area, the gas adsorption methods have the widest range of application. The experimental basis of the gas adsorption method is the recording of the adsorption isotherm of an inert gas (usually N_2) on the solid substance to be investigated in the pressure range of incipient multilayer adsorption. From the isotherm curve, one calculates the number of gas particles required to form a monomolecular layer on the solid substance. For example, non-local density functional theory (NLDFT) models are used to determine the porosity of a sample – pore size and pore size distribution – from measured gas adsorption isotherms.



This advanced NLDFT method allows you to determine the pore size distribution of your sample using two isotherms. In this example, CO_2 adsorption (green) at 77 K and N_2 (red) are used to calculate a single pore-size distribution. You do not have to cut and paste distributions from CO_2 and nitrogen – a single distribution is determined using both isotherms.

Figure 1: Principle of NLDFT for adsorption of CO_2 and N_2 © micromeritics

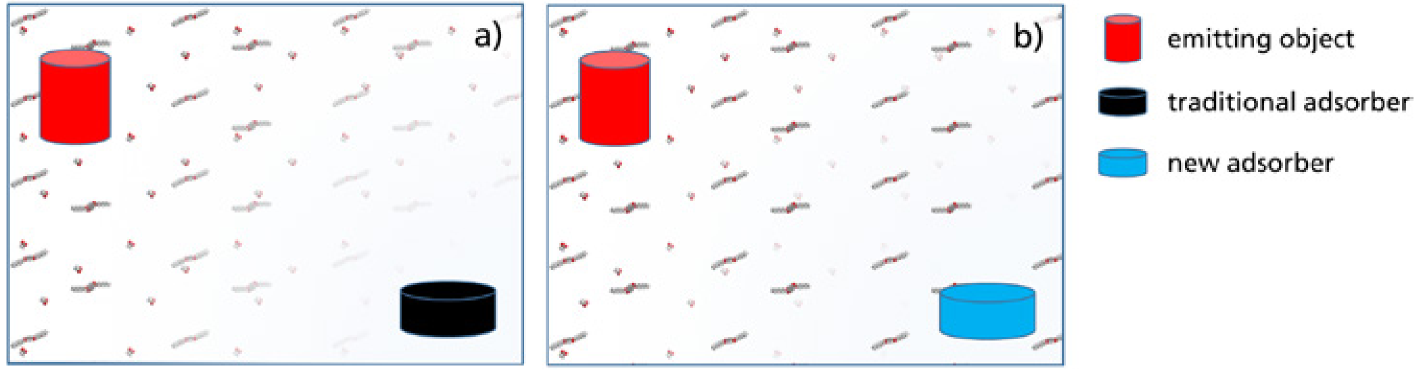


Figure 2: Schematic representation of the adsorption of volatile substances emitted by an object when using a traditional adsorber (a) in comparison with using a new and more specific adsorber (b) © Fraunhofer IAP

The adsorption of substances on surfaces is an equilibrium process. The efficiency of the adsorption of a particular substance is largely determined by the strength of the interaction between the molecules of the adsorbed substance with the surface. Active carbon has a rather broad spectrum of substances it interacts with sufficiently well. This spectrum can be influenced by modifying the surface (see below).

For some art objects the presence of certain molecules in the surrounding atmosphere is particularly destructive while others are not harmful at all. For example, cellulose acetate (CA) is plastic material, which was used for museum objects. When degrading it emits acetic acid, which in turn, accelerates the degradation. It is advisable to remove acetic acid from the atmosphere as quickly as possible. On the other hand, CA can contain volatile plasticizers. The loss of the plasticizer turns the soft into a brittle material. In contrast to the acetic acid, the plasticizer molecules are better not removed from the atmosphere since this would support the evaporation of these molecules from the object. For such cases, it would be good to have an adsorber, which selectively adsorbs acetic acid while it does not adsorb the plasticizer (see Figure 1).

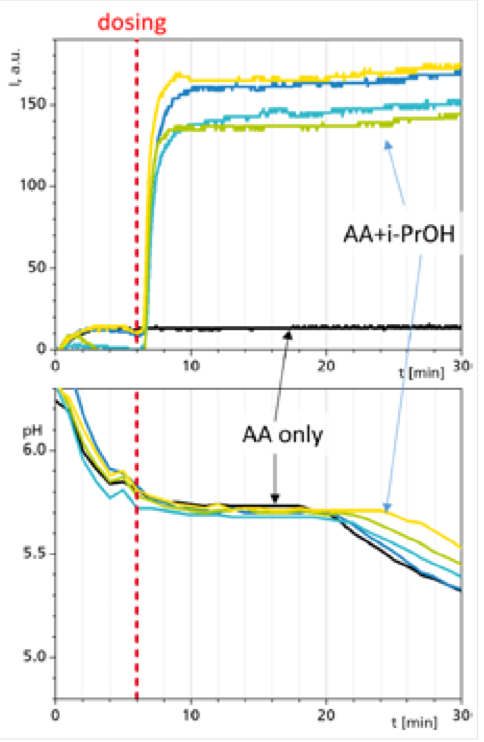
Coating, modification

The properties of porous materials can be tailored to the specific demands of an application by additives mixed in the bulk or by coating the pore surface. For example, the properties of the activated carbon can be modified with various metals and oxides. Alternatively, the pore surfaces are altered by adsorbing substances e.g. from liquid solutions. A treatment with highly energetic chemical species of a low-pressure plasma represents another viable approach, which by itself modifies the adsorption properties of an adsorbent and allows for a covalent bonding of modifying molecules.

In the project, activated carbon was treated with oxygen plasma and coated with an amino functional polymer in order to obtain more specific adsorbents. These materials are supposed to adsorb acidic vapors as acetic acid while it adsorbs less of organic vapors.

The effect was shown on a polyethylene powder, which was functionalized with the amino-polymer. In an experiment, a feed gas was blown over the powder bed. At a certain moment in time a mixture of acetic acid and isopropanol was added to the gas stream. While the isopropanol was detected very quickly after injection at the exit of the powder bed the acetic acid was adsorbed. It took a while until the adsorbing powder was saturated with acetic acid. Only after this delay the acid was detected at the exit of the powder bed (see Figure 3).

Figure 3: Detection of various concentrations of acetic acid (AA) and isopropanol (i-PrOH) in the feed gas (air), which was passed over a bed of amino-functionalized polyethylene powder (i-PrOH gives a positive sensor signal, AA lowers the pH value of a sensing water reservoir) © Fraunhofer IAP



1.2 Parylene coatings for the conservation of film material

Jakob Barz (Fraunhofer IGB)

Introduction

When artificial polymers started their big success story in the mid 19th century, hardly anyone thought that these objects as well as their successors would be later seen as an important part of cultural heritage and modern history. Old historical artwork from the early period, which is not always identified by the visitor as being made of polymer, can be found for example in castles. Examples are the replacement of ivory by Celluloid, silk by Rayon, or Bakelite with its ebony-like noble appearance in artefacts. Today, exhibitions and whole museums are dedicated to daily-use objects from various periods of great success story of polymers.

Besides replacing Ivory in exotic applications like artefacts and billiard balls, Celluloid was used as early film material. Due to flammability issues, it was replaced by Cellulose Acetate (CA) in the 1920s. In addition to much higher safety, this material also offers a better stability against bacteria and fungi due to the acetylation. However, Cellulose Acetate is prone to autocatalytic deterioration: following initial deacetylation due to different mechanisms which are still under discussion, free acid is produced which causes further decay of the material. Thus, in order to conserve Cellulose Acetate, it is crucial to both carefully control the storage conditions during the whole time and further protect the material from pH changes as well as humidity. In this contribution, the encapsulation through a chemical-vapor deposition (CVD) process is presented as a method to preserve Cellulose Acetate.

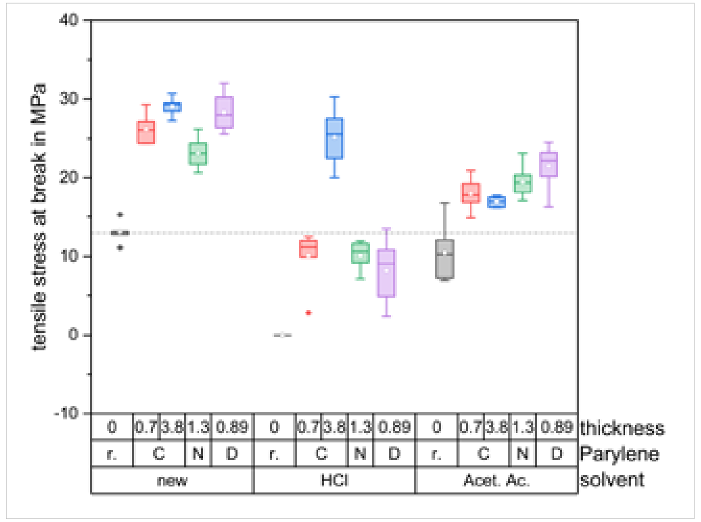
Materials and methods

The CVD coatings were deposited in a vacuum chamber and consisted of Parylene-C, Parylene-D and Parylene-N. Prior to examining the barrier properties on Cellulose Acetate itself, different types of paper were used as substrates in order to separately study the chemical stability, sealing capability, the enhancement of mechanical strength and effect on the optical properties of the coatings.

Results and discussion

An extract of results for silk paper (20 g/m²) after exposure against acids for 48 hrs. is depicted in Figure 4. As can be seen, Parylene is capable to maintain the mechanical strength of the paper samples even in 10% HCl. This effect is more pronounced at high coating thicknesses, whereas the type of Parylene does not show a significant effect.

Figure 4: Mechanical test results of Parylene coated silk paper before and after 48 hrs. exposure against test fluids © Fraunhofer IGB



Additional color measurements on Parylene coated paper were carried out. Any change in color below ΔE* = 1.5 is not visible to the naked eye. Two representative coatings exhibiting good performance in the mechanical tests, Parylene C showed ΔE* = 0.2 and 0.4 for 0.7 µm and 3.8 µm Parylene thickness, respectively. Finally, samples of Cellulose Acetate have been coated and tested in blue-stained acetic acid (100%).

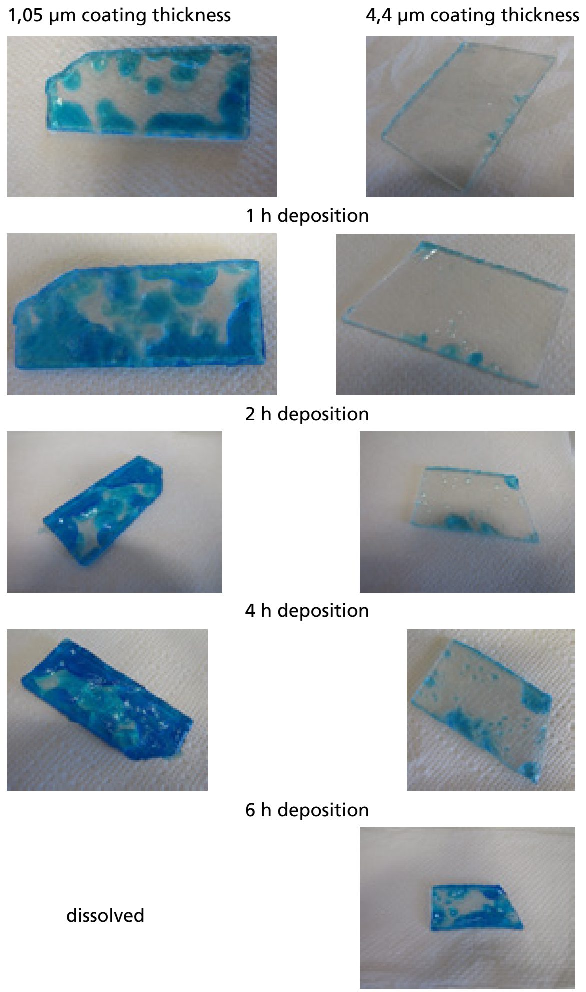


Figure 5:
Exposure of Parylene-coated Cellulose Acetate against pure acetic acid stained with Methylene Blue. Uncoated material immediately dissolves and therefore, a negative control cannot be shown. © Fraunhofer IGB

The above figures demonstrate that Parylene-C is capable of at least delaying deterioration for a long period of time. It was found that typically penetration through the barrier starts at the edges of the samples as they were not perfectly smooth. This effect is more pronounced at low coating thicknesses and has to be kept in mind when considering the conservation of film fragments in the future. At the same time, artificial aging tests show that typical emissions due to deterioration of Cellulose Acetate are significantly reduced and thus, exposure of adjacent exhibits against acetic acid and other VOCs can be avoided.

Conclusion

As has been demonstrated, Parylene-C coatings are suitable for both enhancing the mechanical properties of labile material and provide a barrier against acids on Cellulose Acetate. Even at a thickness of 4 µm, the optical properties are only slightly affected and thus, Parylene coatings can be considered for further investigations in film conservation.

1.3 ORMOCER®s – inorganic-organic hybrid polymers in conservation

Magdalena Roth, Martin Kilo (Fraunhofer ISC),
Rainer Richter (Green Vault, Dresden),
Katharina Klein (freelance conservator, Berlin)

Introduction

ORMOCER®s (organically modified ceramics, see Figure 6) are hybrid polymers combining inorganic and organic structures through the hydrolysis and condensation of silicon and metal alkoxides as well as organo(alkoxy)silanes. Through a sol-gel process, colloidal solutions are generated initially. Thereby low-molecular oligomers evolve that can subsequently be processed to high-molecular products. The final material properties can be adjusted to the current conservation standards by the choice of respectively functionalized starting materials. In contrary, common commercially available polymer-based materials are not designed to conserve objects of our cultural heritage in the long term. Hence, those materials often suffer from unsuitable adhesive strength, defective elasticities and poor ageing properties such as chemical changes, discoloration (mainly yellowing) and restricted reversibility (Horie, 2013; Bierwagen et al., 2003).

ORMOCER®s for the conservation of glass, glazed bricks, metals, and enamel

Following on from earlier developments in the field of glass bonding (Schmidt et al., 1986-1; Schmidt et al., 1986-2) the Fraunhofer Institute for Silicate Research (ISC) designed new materials based on hybrid polymers in the 1990s. Over the past decades various ORMOCER®s that were initially developed for industrial applications have been modified in their molecular structure in such a way that they can be used under ambient conditions in conservation and can thus be used as a consolidant or transparent coating for glass & glazed bricks (Glass-ORMOCER®, ORG), various metals (Bronze-ORMOCER®, ORB), and enamel (Enamel-ORMOCER®, ORE – a specific mixture of ORG and ORB (Wittstadt et al., 2019; "Enameled gold in the Green Vault", 2018) (see Figure 7). The resins are dissolved in a medium-polar solvent or solvent-mixture. The choice of solvent as well as the solids content can be adjusted to the respective treatment and lies in the range of approx. 4 to 40% (wt/wt). Over the past decades it was shown that these hybrid polymers have a favorable consolidating effect, due to their inorganic-organic character, thereby providing good adhesion to different surfaces and permanent elasticity, so that excellent treatment results have been achieved in terms of visual appearance, color impression and long-term stability for damaged glazings (Bulian, 2019; Bulian, 2022; Radujkovic, 2000; Yoshida, 2004; Probst, 2003; Schwarz, 2005) as well as precious gold enamels, such as those found in the collection of the Green Vault, Dresden (Richter, 2000).

Figure 6: Schematic composition of ORMOCER® hybrid material © Fraunhofer ISC

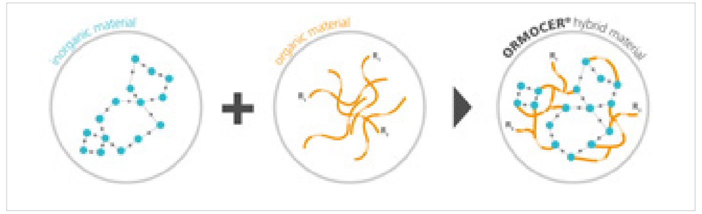
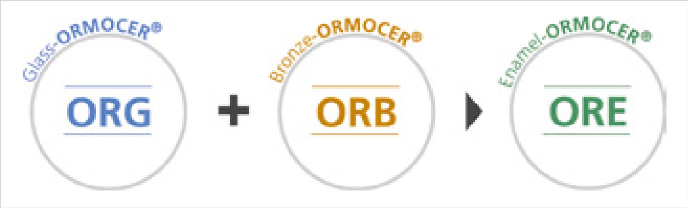


Figure 7: Overview of available ORMOCER®s for the conservation/ restoration of glass glazed bricks (Glass-ORMOCER®, ORG), metal (Bronze-ORMOCER®, ORB) and enamel (Enamel-ORMOCER®, ORE) © Fraunhofer ISC



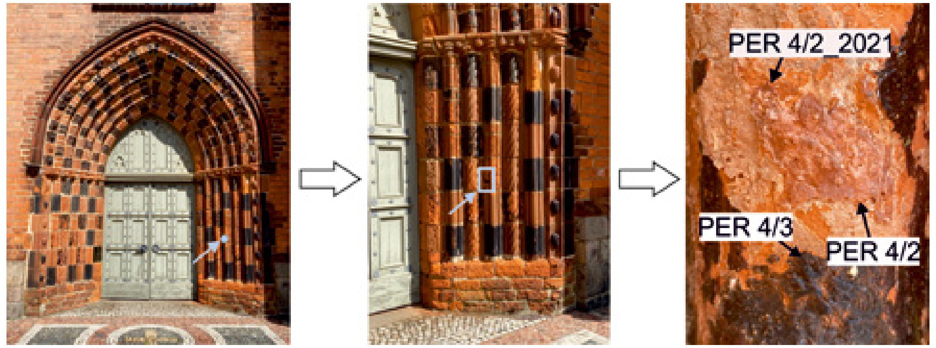
Evaluation of the long-term stability of Glass-ORMOCER® on outdoor objects

Glass-ORMOCER® (ORG) was originally developed for the conservation of medieval glass. The colorless material can be used as a consolidant or as a (transparent) coating on glass objects as well as glazed bricks. The material is reversible, has an optimized elasticity when dry, is easy to use and does not show discolorations. Glass-ORMOCER® has been applied on outdoor objects such as Cologne Cathedral or Erfurt Cathedral, ever since its invention almost 30 years ago. Properties such as reversibility, surface adherence, yellowing, and elasticity and thereby long-term stability of a coating that is to be applied outdoors is very elaborate to evaluate since they might change over time depending on the environmental conditions. With artificial weathering in a climate chamber, it is only possible to draw conclusions of how the material might behave over a certain time period under controlled conditions. However, it is impossible to emulate the outdoor environmental conditions accurately, since in real atmospheres, trace composition, dust and several other materials are found which are not considered in artificial weathering experiments. Therefore, the most reliable approach on the evaluation on a material's long-term stability is an on-site analysis.

St. Jacobi Perleberg

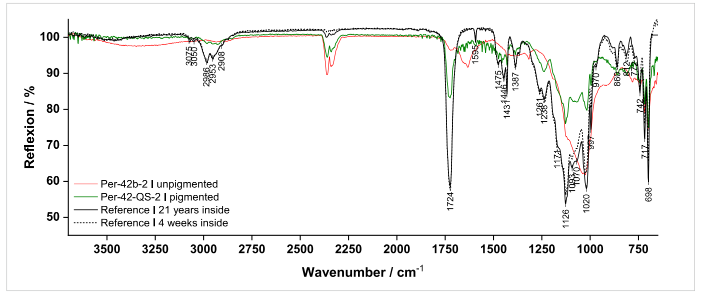
The church is a cross-vaulted brick building from the first half of the 15th century and was built on the remains of its predecessor building from the 13th century. The nave has two portals with late gothic decorations on each side (north and south). The four portals differ however in shape and displacement of the glazed and unglazed bricks as well as in the impost. The portals also differ in the condition of the brick material. The fundamental types and degree of damage are thereby differently marked (Schwarz, 2005). The main damage factors are suspected to be humidity and salt exposure. Studies have revealed that the east portal of the south side is most affected by water soluble ions (sulphates, nitrates, chlorates) (Freyburg, 2001). The analysis of the non-corroded glazing revealed that it is characterized by a high amount of lead (PbO_2, app. 30-51 M%) as well as silica (SiO_2, app. 29-41 M%) (Mottner, 2002). The glazings show a strong degree of lead depletion. The low firing temperature was assumed to be responsible for the observed damages such as tensions, cracking and corrosion of the glazing (Schwarz, 2005). Selected areas of the east portal (south side) have been treated with Glass-ORMOCER® in 2005 in the framework of an DBU Project (Schwarz, 2005). Prior to this a research thesis examined the best recipes for the planned treatment on test specimens (Probst, 2003). These specimens were either disposed to outdoor weathering over the past 17 years or kept inside and thus are excellent study objects for a comparative analysis of the materials behavior.

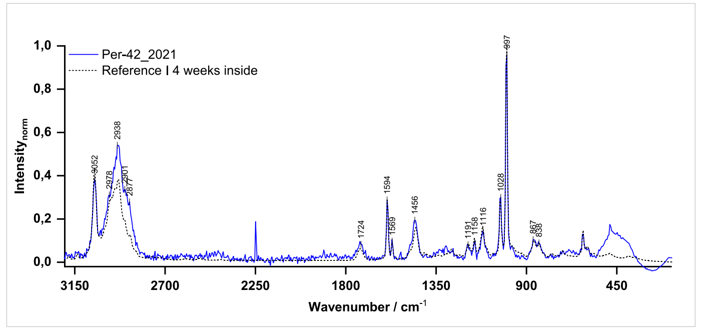
Figure 8:
East portal (south side) sampling area is highlighted (left), detail of the side of the portal with highlighted sampling area (middle), close-up of the sampling area: PER 4/2: unpigmented ORG; PER 4/3: pigmented ORG (right)
© Fraunhofer ISC



In order to analyze the coatings' constitution of the exposed ORG on site, several different types of samples were examined. Due to the rough and uneven state of the sample that was taken in 2021 the micro-FTIR-analysis was limited (FTIR: Fourier Transform Infrared spectroscopy, see Figure 9: very low resolution of the analyzed sample Per-42b, red). Nevertheless, it was possible to measure a sufficiently resolved spectrum of samples taken in 2019. However, those samples are embedded in epoxy resin which complicated the evaluation due to overlapping signals of the embedding material. The results are shown in Figure 9. It was however possible to record a micro-Raman-spectrum of the sample taken in 2021 (see Figure 10).

Figure 9: FTIR-spectra of pigmented and unpigmented ORG applied on the east portal (south) of the Church St. Jacobi in Perleberg. The spectra were compared to reference materials (different batches) that were stored inside for either 21 years (black solid line) or 4 weeks (black dotted line). The spectra were recorded with a ThermoFisher Micro-IR-Spectrometer (Nicolet 6700 equipped with a Nicolet continuum FTIR microscope). © Fraunhofer ISC



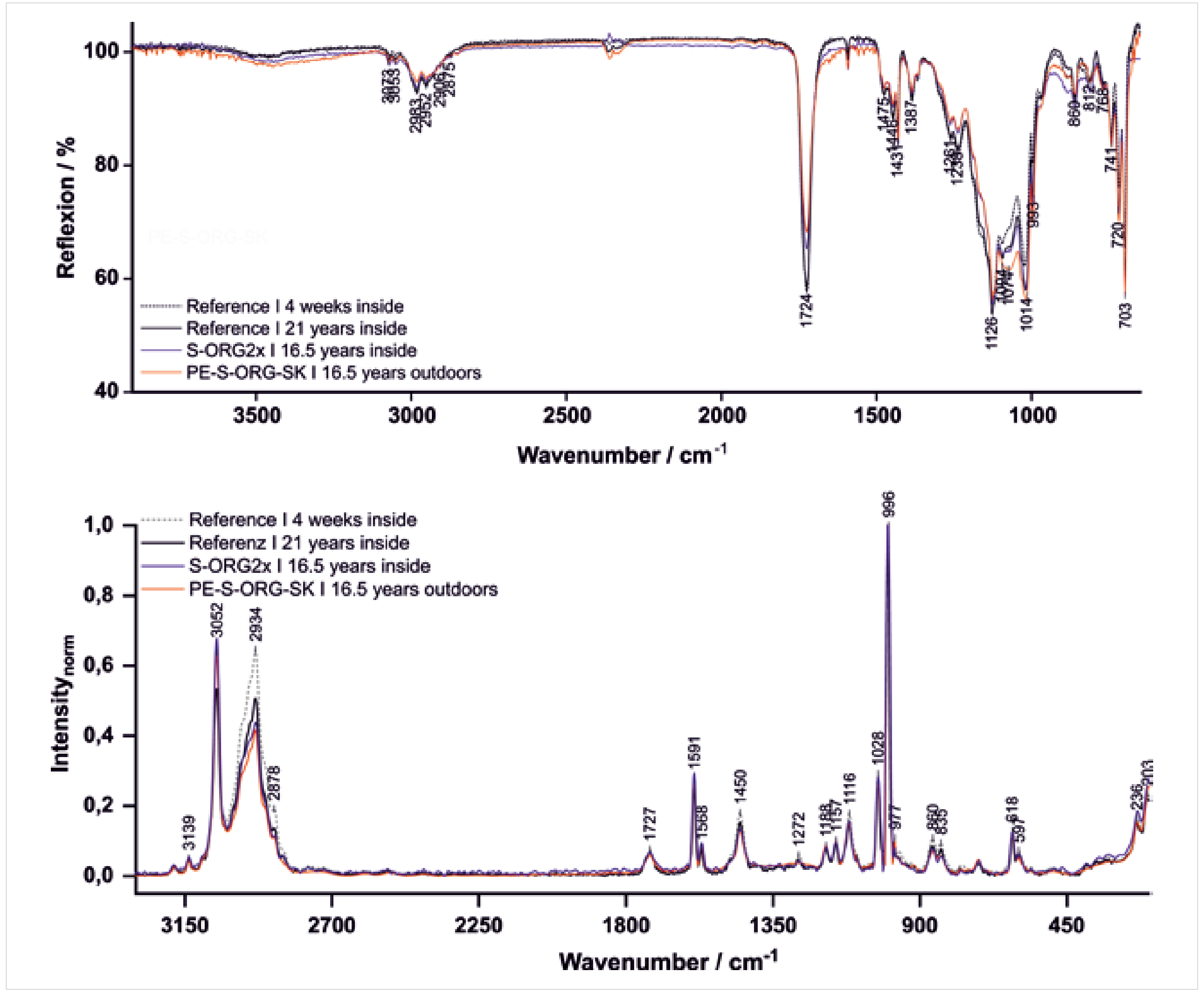


Both the micro-IR as well as the micro-Raman analysis showed that – within the limitations of these methods – no major alteration of the material could be determined. These findings were further supported by the analysis of the sample material that was prepared within the research thesis of thesis of Thiele-Wittig (2005): Thiele-Wittig: none of the spectra shows new bands that might have resulted from oxidation processes. Moreover, no significant peak-shifting could be detected suggesting the high long-term integrity of the material even when exposed outdoor. However, it should be taken into account that oxidation products might overlap with the original bands. In 2001, Chiantore & Lazzari analyzed the photo-oxidative stability of Paraloid®B72 (among other). The oxidation of the product would result in reduced intensities of the C-O-stretching band (1724 cm^{-1}) and increased intensities of the bands in the region of 3000-2850 cm^{-1}, but no new bands were reported. The latter is explained by an increase of OH-groups due to the formation of carboxylic acids. Had an oxidation occurred one would also assume the formation of new bands at around 1710 cm^{-1} (ketones) and 1800 cm^{-1} (anhydrides), none of which could be detected neither on the Perleberg samples nor on the specimens. Since the reference material is not from the same batch as the material that has been applied in the past, it is most difficult to draw unambiguous conclusions. One should also note, that the resolution and band intensity does depend on the respective spectrometer. Even if there was data available from past analyses, they cannot directly be compared to currently measured spectra.

However, since the IR- as well as Raman-analysis could not determine major structural changes, it can be assumed that the materials show excellent long-term stabilities.

Figure 10:
Raman-spectra of ORG applied on the east portal of the Church St. Jacobi in Perleberg. The sample Per-42_2021 was taken in 2021 (blue line). The spectrum was compared to reference material (different batch) that was stored inside for 4 weeks (black dotted line). The spectra were recorded on a WITec Raman-Microspectrometer using a 532 nm laser. © Fraunhofer ISC

Figure 11 top: IR-spectra of ORG applied almost 17 years ago on two differently pretreated specimens (colored lines) compared with reference samples (black lines). Bottom: Raman-spectra of the same samples recorded by Dr. Bernd Bleisteiner and Dr. Christoph Lenz (HORIBA scientific) with a LabRAM SoleilTM Raman Microscope using a 532 nm laser © Fraunhofer ISC



New perspectives for the application of Enamel-ORMOCER® in conservation

Enamel as a composite material of special glass with various metal oxides on top of metal offers, apart from its markedly decorative nature, unique mechanical and chemical properties quite different from the properties of its separate components. Various damages to historic enamels, such as cracking, flaking, and the occurrence of specific corrosion processes require appropriate preventative and active conservation measures. First time in the history of enamel conservation, systematic investigations were carried out in the course of a two-part DBU research effort between 1994 and 1999 (Müller, 1999; Müller, 1995; DBU-Abschlussbericht AZ 09715/01, 1999; BAM, 1995). As main participants cooperated the Federal Institute for Materials Research and Testing (BAM), the Fraunhofer Institute for Silicate Research (ISC) and the Green Vault of the Dresden State Art Collections (SKD) in order to identify any criteria that proved significance to the long-term preservation of the endangered enamels (see Figure 12) in the treasury of the Green Vault. The following tandem system has clearly turned out to be most promising (Engemann-Wendt & T. Waurik, 2010; Richter, 2001): A favorable indoor climate, such as stable low humidity levels, air circulation and control of gaseous pollutants, which slows down the harmful effects of intrinsic corrosion processes of the instable glass materials. And secondly, the application of an innovative consolidating medium, which is able to rebind the fractured structures of the composite material, some of which are enriched with hygroscopic corrosion products. Based on a test procedure in which an extensive selection of traditional and innovative consolidants were applied to material-accurate replicas of baroque gold enamels, the newly designed Enamel-ORMOCER® (ORE) was eventually chosen due to its outstanding properties. ORE is thus a tailor-made conservation material for enamel objects and its most characteristic features are:

- colorlessness / transparency,
- low viscosity (in solution),
- solubility in moderately polar solvents,
- excellent adhesion to metal, glass, and corroded glass surfaces,
- low degree of elasticity and minimal softness (after curing),
- refractive index (n_D ca. 1.53),
- ageing stability,
- re-solubility, and
- non-toxic (respectively low-toxic) solvents.

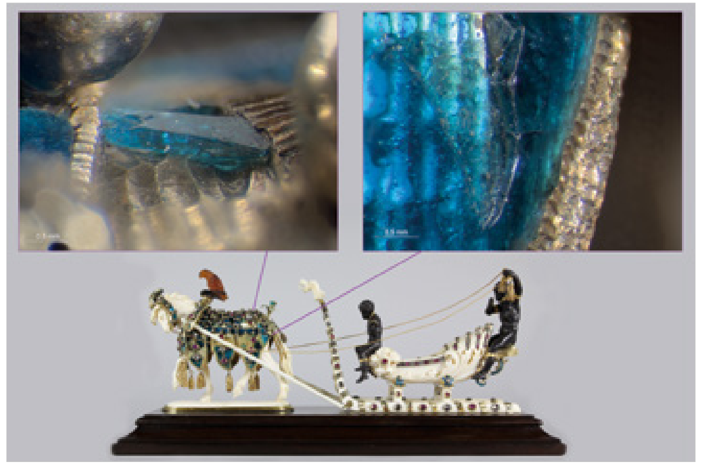


Figure 12:
Horse sledge, early 18th century, Green Vault, Inv.-No. VI 194. Consolidation of flaking enamels on gold alloy with ORE in 2002. Visually unaltered condition as image documented in 2017 © K. Klein

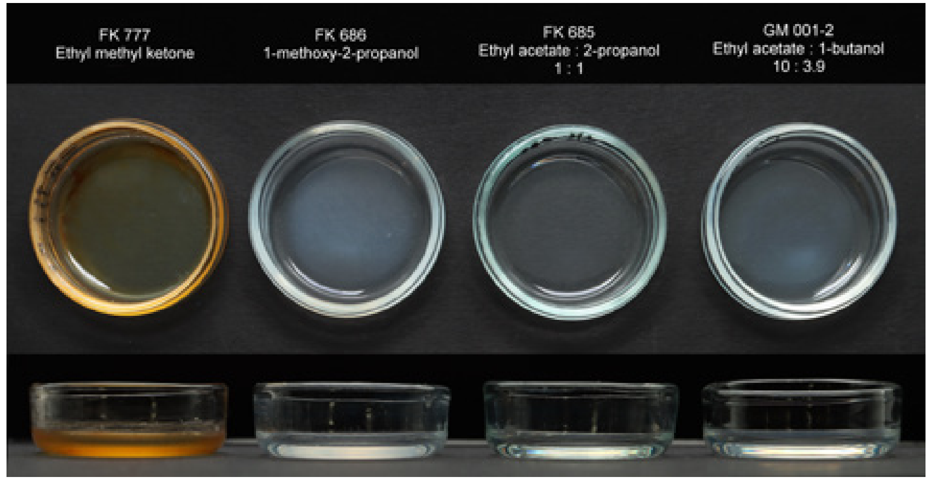


Figure 13:
Samples of solid ORE (alkoxy) in Petri dishes after evaporation of their respective solvents, 2022
© SKD / R. Richter

While the tandem preservation concept could be implemented stepwise through the reopening of the permanent exhibitions of the Green Vault 2004 and 2006 in the reconstructed Dresden residence, the availability of ORE could not be guaranteed any longer for conservation purposes since 2011 due to unpredictable circumstances, i.e. a dramatic increase of impurities in the starting materials, in the sol-gel based synthesis process. Cloudiness and even yellow discoloration developed shortly after the start of the adhesive setting process. Therefore, the Fraunhofer ISC carried out a precise quality control of the monomers supplied by the chemical industry and critically reviewed the multi-stage synthesis process in order to ensure the reproducibility of the manufacturing process: The original synthesis route depended on toxic chlorosilanes as starting materials, resulting in the release of gaseous hydrochloric acid during the synthesis. In a novel approach the chlorosilanes were successfully replaced by less critical alkoxysilanes. Changing the synthesis route was however a very complex process since the reaction behavior of the silanes changed drastically when the strong electronegative chlorine substitutes were exchanged with the respective alkoxy groups. Therefore, it was necessary to adjust all further synthesis parameters. This demanded a meticulous analysis not only of the starting materials but also of the final products as well as possible by-products using FTIR-, Raman- and NMR-spectroscopy (Wittstadt et al., 2019). After reassuring the reproducibility of the synthesis, the material had to be tested for its properties and further optimizations, especially regarding the choice of solvents, had to be carried out.

For this reason, Fraunhofer ISC and the Green Vault of the SKD cooperated once more in a research project that started in 2015. A profound evaluation of the tandem preservation concept of the Green Vault in 2017 confirmed the efficiency of the air-conditioned and pollutant-filtered showcases as well as the long-term stability (macroscopic and microscopic evaluation) of enamel consolidation measures taken mainly 15 to 17 years prior to this investigation (see Figure 12) (Klein, 2017). New batches of ORE solutions (14% and 40% solid content) became available first in early 2017, some with visually water clear appearance, which even slightly surpassed their predecessors. However, observations during the hardening process revealed a much greater impact of the chosen solvent(s) on the discoloration of the cured material. The preferential use of the solvent methyl ethyl ketone until the year 2011 was terminated due to the identification of autooxidation products of the amine hardener. Moreover, side reactions between the solvent (ketone) and the hardener (amine) resulting in an imine formation were identified as a likely source for the yellowing of ORE solutions (see Figure 13, FK777).

More than 30 different solvents respectively solvent blends were tested. However, as a thick film application, the majority of the samples temporarily or permanently developed opaque cloudiness or opalescence. Some turbidities developed very dynamically, some decreased and some increased during the drying process. In summary, it can be concluded that a wide range of medium-polar solvents is able to form clear solutions with the ORE but only few solvents are suitable to transfer the solution into a visually water clear solid thick film.

Although these effects are observed to a much lesser extent in thin films, the more practically relevant case in a consolidation treatment, the best results were obtained for the following system: 1-methoxy-2-propanol with or without admixture of ethyl acetate provided excellent albeit slowly drying samples for ORE which is based on the chlorosilane synthesis. In contrast, the alkoxysilane-based samples dried much more transparently when ethyl acetate containing alcohols such as 2-propanol or 1-butanol were used (see Figure 13, FK 685, FK 686, GM 001-2). These variants are faster curing, which is desirable in particular for consolidating measures. Another very important factor in terms of sales and application is the fact that the required degree of dilution of ORE can be adjusted by the conservator himself prior to the addition of the hardener.

Further details of the results of this cooperation, also with regard to the use of ORE in other areas of application than in enamel conservation, can be found in the literature (Wittstadt et al., 2019; Richter, 2019; Richter & Klein, 2020).

Summary and outlook

Inorganic-organic hybrid polymers, especially ORMOCER®s that were specifically designed to meet the demands of today's conservation standards, can be used for the conservation and restoration for various materials such as metal, glass, enamel, and glazed bricks. One major criterion when choosing an appropriate conservation material is its sustainability, which is closely linked to the material's long-term stability. The latter is especially challenging when the material is applied on outdoor objects as well as on indoor objects exposed to critical climatic conditions where the environmental conditions are uncontrolled. The evaluation of Glass-ORMOCER® that has been partially applied app. 20 years ago on St. Jacobi's (Perleberg, DE) east portal has revealed that no detectable intrinsic molecular structural changes have occurred during this time. The development of a novel synthesis route that is independent of the use of toxic chlorosilanes allowed for the use of less critical starting materials thereby also facilitating the future scale up procedure and will help to broaden the application of the ORMOCER®-based materials among the conservation practice.

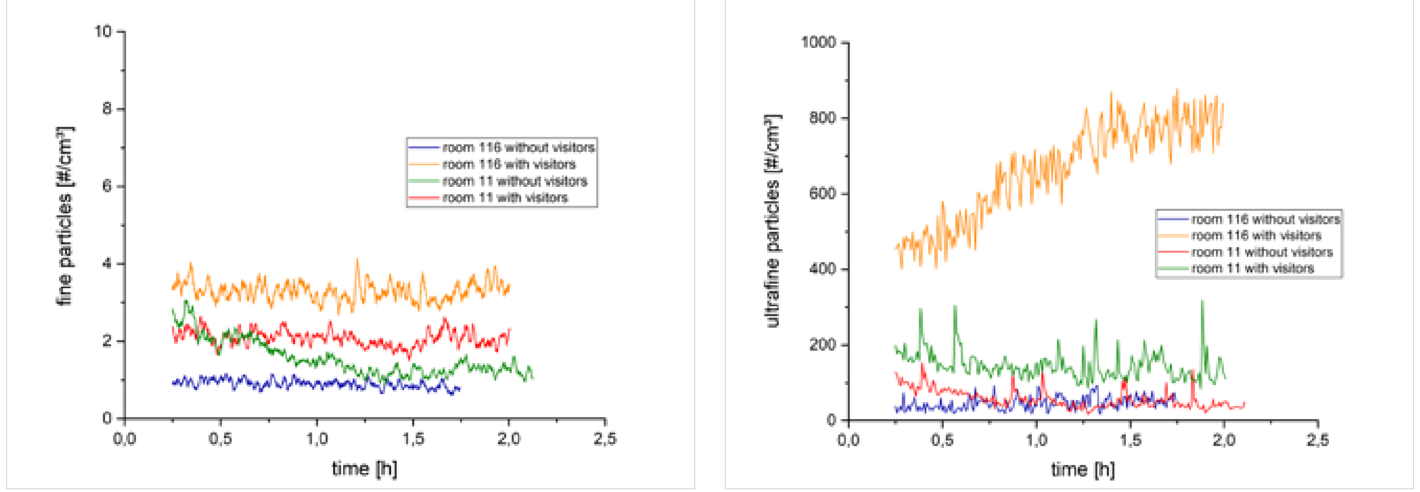
Since 1994 the Dresden State Art Collection and the Fraunhofer ISC have been cooperating in order to develop a tailor-made conservation material for enamel objects. Thereby Enamel-ORMOCER® was developed by the Fraunhofer ISC and its properties where continuously and thoroughly tested by the SKD to further improve the long-term material stability. However, the novel synthesis approach (2017-2019) has caused changes in the materials behavior, but thanks to the cooperation between the Fraunhofer ISC and the SKD, which included a meticulous adjustment of the solvents, a once proven conservation material (colorless, transparent, separately dilutable and long-term stable) has thus been made accessible again. From now on a quality-controlled synthesis process of the material ensures constant composition of ORG and ORE solutions, unlike usual commercial products where processes and compositions can easily change. Future research will focus on the scale-up of the Glass-ORMOCER® synthesis as well as further property characterizations such as the ease of reversibility of Enamel-ORMOCER®.

1.4 Particles and dust

Alexandra Schieweck (Fraunhofer WKI)

In colloquial speech, the term dust is mostly applied for visible dust settled on surfaces. However, it has to be differentiated between sedimented dust, commonly named house dust, and suspended airborne particles. Airborne particles are mainly characterized by the physical parameters number, mass and surface area. Dust sedimented on surfaces of cultural assets might influence the aesthetic appearance and might also contribute to corrosion processes. As those items on display might require regular cleaning, cautious handling is necessary in order to avoid abrasion due to mechanical cleaning activities. From a health perspective, the size of the dust particles is an essential parameter regarding the uptake into the human body. Particles with a diameter above 10 µm (coarse dust) are generally remaining in the nose and throat region. Smaller and smallest dust particles (fine particles, ultrafine particles) can penetrate into the lungs (Schieweck and Salthammer, 2014). In indoor environments, fine ($PM_{2,5}$) and ultrafine particles (UFP) are mostly focussed. Main particle sources in museum environments are the infiltration by outdoor air, the release by ventilation systems (mechanism, air exchange rate) and the ingress by clothes and shoes of visitors (natural/synthetic fibres, street dirt). By walking through historical rooms, visitors might also trigger the resuspension of particles held in textile floor coverings. Thus, most conservators are concerned about dust sedimentation on surfaces of display cases and collection items. Figures 14 shows the concentration of fine particles and ultrafine particles over a time span of 2.5 hours in two different exhibition rooms in the Gemäldegalerie Alte Meister der Staatlichen Kunstsammlungen Dresden (Old Masters Picture Gallery, Dresden State Art Collections). Both rooms are located in the first floor near the staircase. Before the gallery rooms have been renovated, the air was circulated from the top to the bottom for ventilation purposes. After renovation, the airflow was reversed (bottom to top). Measurements in room 116 were performed before renovation, whereas the experiments in room 11 were carried out after the new installation system has been installed. In both cases, fine and ultrafine particle concentrations were in the lower range with slight differences when the gallery was closed

Figure 14: Concentrations of fine particles (left) and ultrafine particles (UFP, right) in two gallery rooms of the Gemäldegalerie Alte Meister der Staatlichen Kunstsammlungen Dresden. Room 116: before renovation, room 11: after renovation (displacement ventilation) © Fraunhofer WKI Braunschweig



and open (without/with visitors). Before renovation, differences between opening and closing of the rooms were larger (room 116) than after renovation (room 11). With displacement ventilation, particle concentrations are in a very narrow range irrespective of whether the gallery is open or closed. For a better understanding of the measured particle levels, UFP concentrations in outdoor air commonly vary between 1.000-10.000 #/cm^3 in dependence of the weather conditions.

However, there is no binding definition of the term “house dust”. In contrast to airborne particles, all types of particles which can be found in deposited form on indoor surfaces are included in the term “house dust” with particle diameters from the micrometer range to the range of several millimeters. Thus, house dust consists of a complex mixture of different particles, such as e.g. hair, skin cells, fibres from clothing, textile floorings and furnishing, as well as inorganic materials, such as e.g. soot particles, sand, clay, and pollen, fungal spores and microorganisms. House dust is primarily examined with regard to the detection of biocide agents bound to dust particles. For this, information regarding the age of the dust (old dust or fresh dust), the sample preparation and the sampling technique are important (Schieweck and Salthammer, 2014). House dust samples can be subjected to a screening of a wide range of different biocide agents in one analytical step, which is therefore a promising, fundamental and cost-effective analytical approach which, thus, might be required as first step by specific test protocols, such as the German Pentachlorophenol Prohibition Ordinance (PCP-V).

1.5 Thermal analytics

Yvonne Kasimir (Fraunhofer ICT)

Thermal analysis belongs to the large field of materials science. It investigates how changes in temperature can affect material properties. Physical and chemical properties of pure substances or mixtures of substances are measured as a function of temperature or time. Typical methods of thermal analysis include thermogravimetry and differential scanning calorimetry.

Thermogravimetry (TGA) is an established method for the thermal characterization of solid and liquid materials and is used to investigate physical processes and chemical reactions associated with mass changes. In TGA, the mass change of the analyte is measured as a function of temperature and time in a defined atmosphere. Mass changes occur, among other things, during evaporation, decomposition, chemical reactions and magnetic or electrical transformations. By coupling the thermobalance with a mass spectrometer, the gases released from the samples at certain temperatures can be analyzed and information about the decomposition behavior of materials (plastics, composites, fuels, building materials, etc.) as well as the release of emitters can be obtained.

Differential scanning calorimetry (DSC) is a method that measures the amount of heat released (exothermic) or absorbed (endothermic) by a sample during heating or cooling, thus providing information about the thermal behavior of the material. The principle of operation is based on the measurement of heat flows between a sample and a reference sample during a controlled temperature programme. The heat flow is recorded as a function of an external temperature change. From these data, information about phase transformations such as melting or solid-solid transformations in crystals can be obtained. Furthermore, with suitable calibration, the specific heat capacity and the crystallinity of polymer samples can be determined, and kinetic investigations of phase transformations can be carried out. In addition to phase transformations and specific heat capacity, other properties that can be determined using DSC include thermal and oxidative stability, the determination of the glass transition temperature (Tg), the purity of materials and the monitoring of ageing processes. With the help of DSC, plastics, paints, adhesives, and organic coatings, as well as foodstuffs and pharmaceuticals, etc., can be characterized.

Within the framework of the FALKE II project, some plastics were used for investigations by means of thermal analysis in order to obtain information on the material properties.

As an example, polyvinyl chloride (PVC), an amorphous thermoplastic, will be presented and discussed below.

Polyvinyl chloride shows a very low mass loss in the temperature range between 120-200°C. The degradation of PVC under nitrogen essentially takes place in two stages. In the first stage between 220-350°C, dehydrochlorination (HCl splitting off) takes place. In the second subsequent stage, chlorinated aromatics are formed. The gradual decomposition of the material usually starts at very low temperatures. The decomposition can be detected via a connected online-mass spectrometer or via Pyrolysis Gaschromatography-mass spectrometer (PyGC-MS). In the present example, HCl was detected in the thermodesorption stage at 260°C in PyGC-MS. Due to its amorphous structure, the PVC only shows a glass transition in the DSC and no melting behavior. From the determined glass transition of 79°C it can be deduced that it is a rigid PVC without plasticizer.

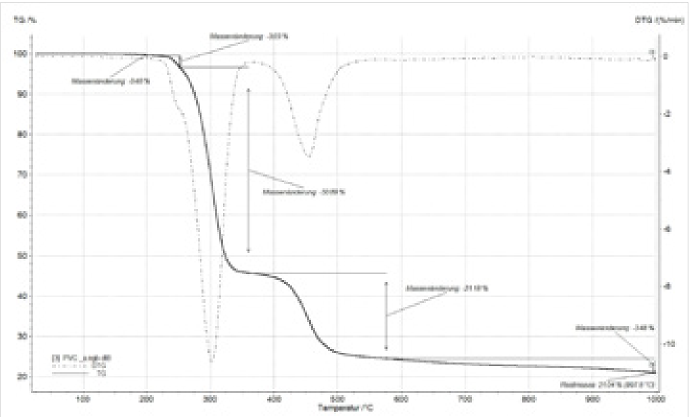


Figure 15: Thermogram of polyvinyl chloride (atmosphere: inert gas) © Fraunhofer ICT

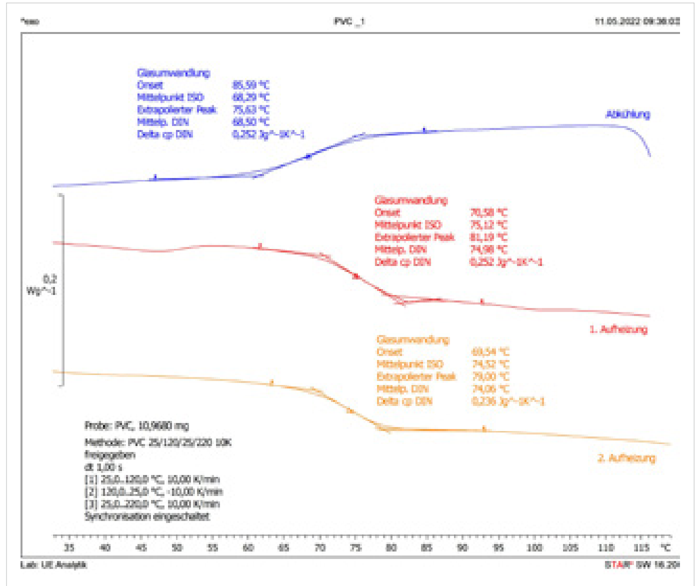


Figure 16: DSC of polyvinyl chloride © Fraunhofer ICT

1.6 Emission test chambers

Alexandra Schieweck (Fraunhofer WKI)

Chamber emission testing is a standardized conventional method to investigate the emission characteristics (emission spectra, source strength) of test specimen in dependence of environmental conditions. Emission tests are therefore established to clearly attribute released volatiles to their sources and to determine the emission profile of a specific material without interfering uncontrollable environmental conditions as the chamber test device is sealed gas tight against the outside. Those kinetic experiments allow the investigation of emissions versus time with regard to temperature T (°C), relative humidity RH (%), air exchange rate n (h^{-1}) and the product loading factor L (m^2/m^3). By aligning these parameters to the realistic indoor environment, the specimen will be used in, experimental data sets provide valuable information about the test specimens emission profile, its source strength, released substances, and curve progression. Moreover, insights are gained about how the emission characteristics are influenced by environmental parameters, which can also include lightning and background pollutants.
Chamber emission tests are carried out with the following goals:

- to screen materials for indoor use in order to classify them according to their emission strength,
- to obtain compound-specific data on various sources as necessary basis for field studies and for evaluating indoor air quality,
- to identify environmental parameters which are influencing the concentrations of volatile organics emitted from a source,
- to simulate as close as possible real indoor conditions which allows conclusions about the degree of contribution of a given source to indoor air quality,
- to obtain emission data to develop and verify mathematical models for prediction of indoor air concentrations, or
- to rank products according to their emission profiles and to develop labelling schemes.

Sizes of emission test chambers range from a few liters to several cubic meters. Thus, room-size large scale chambers (“walk-in” type) with volumes typically between 12 m^3 and 80 m^3 and small-scale chambers with sizes ranging from a few liters up to a few cubic meters are distinguished (Salthammer, 2009; Schieweck and Salthammer, 2014). Chamber emission testing is specified in DIN EN ISO 16000-9:2008-04 and DIN EN 16516:2020-10. For a rapid screening of material emissions and in order to obtain fast information about the composition and level of emissions of volatile organics, reliable microscale devices have been developed which allow emission testing of small sample sizes under different temperatures and air velocities to provide semi-quantitative results (Schripp et al., 2007).

Environmental test chambers have also been used to investigate the filtration efficiency of a broad range of adsorbent media, both under active and passive conditions in order to simulate conditions in showcases with and without forced air exchange, respectively. For the experiments, target substances, which have been representatively selected as ubiquitous airborne pollutants in museum environments, have been dosed into chamber air. Active air sampling was performed in order to analyze the decay rates of pollutant concentrations, namely volatile organic compounds (VOCs), formaldehyde and C_1-C_2-carboxylic acids (Schieweck, 2020).

2.1 Introduction

Frank-Holm Rögner (Fraunhofer FEP)

Much of human cultural identity is based on written records, which rapidly increased in number and distribution after the invention of the printing press. However, the preferred medium of paper poses great challenges to the preservation of written cultural assets. If stored carefully, paper documents can be preserved without loss for 1000 years. However, since the basic substance of paper – cellulose – is an organic material, deviations from the optimal storage conditions cause serious damage mechanisms. In addition to long-term damage caused by mold or other fungal infestations, feeding insects or intensive use by humans, there is increasing damage from individual events such as extreme weather events, fires, and wars. Climate change, which is in full swing, not only influences the frequency of extreme events, but also the long-term effects on the storage conditions of paper documents.

A special case is the paper produced industrially from around 1850 to the 1980s, which is now largely very badly aged and is threatened or affected by paper decay, also known as “acid corrosion”. Mainly due to the choice of raw materials (wood pulp) and the acidic stock sizing (alum), chemical degradation reactions (acidic-catalyzed hydrolysis, oxidation, crosslinking) occur in the cellulose, which reduce the fiber strength and make the paper increasingly fragile and brittle. If there are no treatment measures, the papers will eventually become so brittle that they can no longer be used without causing mechanical damage (cracks, breaks, decay). In addition, the papers yellow after just a few decades due to the lignin contained in the groundwood. From a statistical point of view, this industrially acidic paper, which is threatened by paper decay, now accounts for around 70% of the world’s library and archive holdings. There is a similarly high proportion across Germany.

For the restoration and conservation of paper documents, this results in two main tasks: the stabilization and deacidification of fragmented, brittle objects and the unblocking of blocked objects. This applies to valuable individual objects, mostly in library or museum stocks, as well as many kilometers of archive material on shelves.

Figure 17: War-damaged manuscript Mscr.Dresd.M.28’ Böhmes Codex Oppollensis (dated 1405) © SLUB

Figure 18: War-damaged manuscript Mscr.Dresd.M.28’ Böhmes Codex Oppollensis (dated 1405) © SLUB

2.2 State of the art

Frank-Holm Rögner (Fraunhofer FEP)

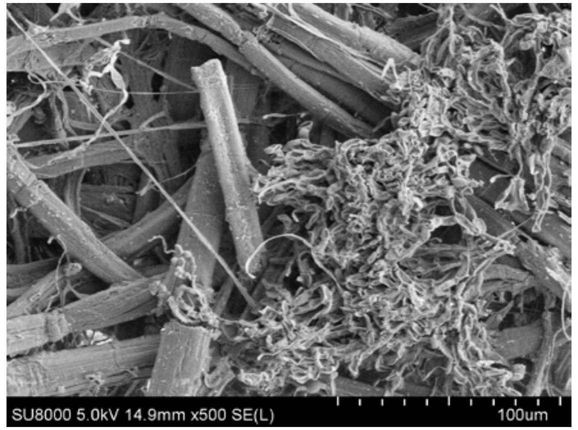
In order to significantly slow down paper degradation or acid hydrolysis as its main cause, mass deacidification processes have been offered by various service providers in Germany for more than 20 years and are constantly being further developed. Depending on the process, the acid contained in the paper is neutralized with different reagents and techniques and a so-called alkaline reserve is introduced to buffer renewed acid formation/effects. As part of a study funded by the German Federal Cultural Foundation to investigate the "Sustainability of mass deacidification of library material", it was demonstrated that mass deacidification of paper that was already badly degraded could no longer stabilize the cellulose. In the worst case, there could even be further mechanical damage to the paper. Accordingly, mass deacidification comes too late for those papers that have already been badly degraded and mechanically weakened.

Papers that are already subject to strong degradation mechanisms due to depolymerization are nowadays countered with other, stabilizing measures against the background of mass substance preservation. In contrast to the mass deacidification process, the stabilizing measures have so far only been possible in the single-sheet process. The principle is the reinforcement of the brittle fiber fleece by fixing it to a stable, preferably inert carrier. A distinction is made between supporting systems that work from the outside and those that work from the inside.

Inert plastic foils or wafer-thin fibrous webs made of cellulose are applied to the paper in a hot or cold process or, for example, by splitting it into the paper and attached using different binders. Paper that has already been badly damaged can be protected from further decay in this way, but the corresponding processes are too cost-intensive for widespread use. Regluing is one way of restoring stability to a weakened paper fleece. The method is based on the historical method of leaf sizing, but today it does not use gelatin, but modern solidifying agents, mostly cellulose ether. This process only has a slight strengthening effect and can therefore only be used on paper that is only slightly damaged. The same applies to fraying, in which, as on the paper machine, a (very thin) pulp is poured over the paper lying on a sieve. Through this process, the fibers fill in the gaps in the paper with newly formed paper. This method is mainly used to fill in missing places in the object. Covering with transparent plastic films is not acceptable for restoration purposes since this type of stabilization is not resistant to aging and even irreversibly damages the treated objects in the long term.

In accordance with the requirements of restoration ethics, the experience gained from restoration practice and the understanding created by science, the idea was formed in the 1960s to close the fractures in the aged cellulose on a molecular level, i.e. on the inside (in situ). The advantage of an "invisible" stabilization on the inside with the simultaneous introduction of an alkaline reserve is obvious. The idea of strengthening paper by grafting on acrylate-based monomers and making it more resistant to aging has existed for more than three decades. However, the results were not convincing from the point of view of restoration (haptics, smell, color change, embrittlement, staining). The main reason for the rejection, however, was the presence of hazardous or toxic residual monomers in the paper.

Figure 19: SEM image, accumulation of fungal spores in the paper fibers © Fraunhofer FEP



In contrast to the large number of restoration approaches in the field of brittle paper, there have so far been hardly any usable methods and tools for processing blocked objects.

For this reason, particular attention has been paid to the following tasks in recent years:

- investigation of blocking mechanisms in preparation for the development of unblocking methods,
- development of methods of extended object identification for highly fragmented or lured objects for comprehensive data collection of the find situation,
- development of approaches for mass digital reconstruction of fragmented objects, and
- development of approaches to digitally support the physical reconstruction of fragmented objects.

Figure 20: Light micrograph, magnification 155x, fungal hyphae and fungal spores on the paper surface © Fraunhofer FEP

2.3 Blocking of war-damaged paper documents

Frank-Holm Rögner (Fraunhofer FEP),
Gerhard Schottner (Fraunhofer ISC)

The biological infestation of historical or modern paper with ubiquitous mold – triggered by improper storage in humid ambient air (e.g. in historical buildings), by war-related events (e.g. extinguishing water after fires) or extreme weather events (e.g. recurring floods on river banks or heavy rain) leads to the degradation of paper through depolymerization and possibly to blocking of printed matter due to excessive growth of fungal mycelium (see Figures 19 and 20).

Cleaning and restoring such printed matter that was improperly stored or insufficiently dried in the past has not been successful to date and requires fundamentally new knowledge of the damage pattern and the underlying mechanisms. This includes in particular intensive examinations of the fungi and microorganisms involved in the damage pattern and their molecular structure. The fungal mycelia (hyphae, spores) interwoven with the paper can then only be removed using very specific (chemical) methods that in no way further damage the paper, but only attack and, if necessary, dissolve the relevant fungal components (especially the stable cell walls).

The knowledge about the molecular structure of fungal cell walls that is already available in the scientific literature can be used to apply suitable, highly specific enzymes, suitable to split (depolymerize, hydrolyze) the polysaccharides (ß-glucans, a-glucans, chitin, etc.) in the fungal cell walls. Due to the complexity and variety of the fungal cell walls of different species that occur in historical and modern damaged papers and printed matter, the development of a potentially suitable enzymatic process for cleaning and elucidating the reaction mechanisms involved and proving its economic viability will require some effort.

The basics for this important process of preserving and restoring valuable printed works and documents are currently being developed in a project funded by the German Federal Environmental Foundation (Deutsche Bundesstiftung Umwelt – DBU) and led by the Saxon State and University Library (SLUB, Dresden) with the partners ZfB (Center for Book Preservation, Leipzig), IHD (Institute for Wood Research, Dresden) and Fraunhofer ISC (Fraunhofer Institute for Silicate Research, Würzburg).

2.4 Hyperspectral Imaging (HSI) for the analysis of historical objects

Wulf Grählert, Florian Gruber (Fraunhofer IWS)

HSI is a combination of spectroscopy and imaging that enables high-resolution spatial and spectral characterization of surfaces. This allows differences in the topology, morphology, and chemistry of the objects studied to be found. HSI can be performed in different spectral ranges and spectroscopy methods (reflectance, transmission, fluorescence, Raman, etc.). Figure 21 shows schematically the setup of an HSI measurement system for measuring the reflectivity of historical objects, consisting of an illumination unit, a motion system for the specimen, and a hyperspectral line scan camera. Hyperspectral imaging can be used in the examination of historic objects, for example to record and preserve their exact appearance and composition, but also to generate new information. Possible applications are, for example, the visualization of hidden drawings under the uppermost layer of paint of paintings and the determination of the materials used (Horie, 2013; Bierwagen et al., 2003; Huang et al., 2016), Schmidt et al., 1986-1; Schmidt et al., 1986-2; Picollo et al., 2020). In addition to the high information density, the fast, non-contact and non-destructive measurement is of particular advantage for the examination of historical objects.

In the FALKE project, HSI was used for the characterization of historical paper samples. Various possible applications were investigated as examples. First, it was shown that hyperspectral imaging can be used to visualize watermarks and sieve texture of papers quickly and non-destructively (Figure 22 a). In particular, HSI in the near-infrared region (short wavelength infrared/SWIR HSI) is suitable for this purpose. In this case, the measurement of an object takes only a few seconds, and no sample preparation is necessary.

It was also investigated whether HSI can be used to characterize different types of paper. For this purpose, 12 papers from different sources were examined using SWIR HSI and it was shown that a reliable classification of the individual paper grades is possible (Figure 22 b). In the future, a paper database could be created to non-destructively determine the paper used for unknown objects.

Further applications of HSI in the examination of historical papers were identified as the detection of water damage, mold, and the success of paper de-acidification, which will be investigated in the future.

Figure 21: Schematic of an HSI measurement system for measuring the spatial reflectivity of samples MU: motion unit, DF: diffuse illumination, L: lens, HSI: hyperspectral camera © Fraunhofer IWS

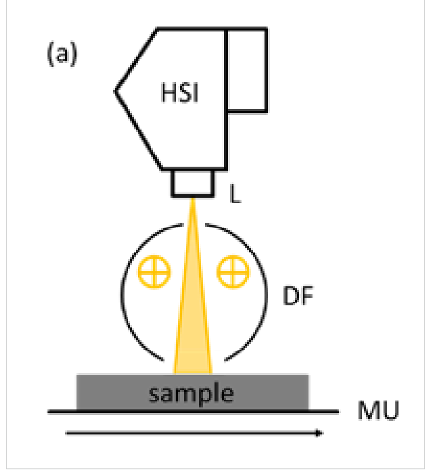
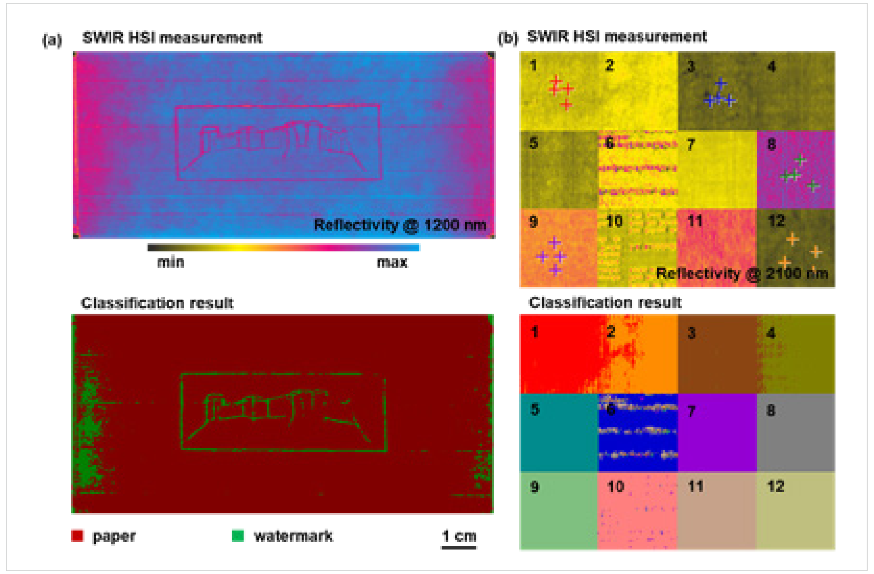


Figure 22: Paper sample with watermark, measured using SWIR HSI and the result of a classification model to detect the watermark (a), SWIR HSI measurement of 12 paper samples and result of a classification of all 12 paper samples (b) © Fraunhofer IWS



2.5 High-resolution Computed X-ray Tomography as a means to qualify damages of historical books

Theobald Fuchs (Fraunhofer EZRT)

X-ray Computed Tomography has the potential to qualify the condition of historical books in a contact-less non-destructive way in three dimensions in order to inspect a book, that has neither be opened up nor even taken out of its protective covers or envelopes. With respect to the achievable spatial resolution, the size of the book has the most influence. With typical dimensions of 10 by 20 centimeters, a cubical volume element (voxel) size of 100 µm can be easily provided. On the one side, this resolution is more than sufficient to resolve single letters within the text plane. On the other side, higher resolution is needed in order to separate single pages in the third dimension, which have typically thicknesses between 80 and 150 µm.

In the case of historical books, which were damaged to varying degree by fire, water and microorganisms, our task is to evaluate which kind of additional information a CT scan can provide. With respect to microorganisms and a conversion of the separate pages into a blocking due to the impact of water, the CT slice images show varying densities within the whole book. These image regions, which appear darker in some cases and partly brighter, seem to be caused by the structural changes within the paper. Potential correlations with the single mechanisms of deterioration need to be investigated further in the near future. In addition, first tests show that parts of the printing are visible in the 3-dimensional X-ray images. This is somehow surprising since the inks do not contain a significant amount of iron particles. Rather the contrast of the letters with respect to the paper most probably results from the difference in density between the ink based on ashes and the background materials.

A major obstacle to really reading the text in CT slice images that result by default from an orthogonal grid of reconstructed voxels, is the waviness of the pages caused by wetness and the subsequent drying process. Here further efforts are in progress to virtually flatten the digital representation of the pages using specialized software. Eventually, we observed a high number of small irregular bright spots inside the paper which could not yet been identified. A possible cause of these very small high contrast particles could be wooden fragments in the paper, metal remains from the paper milling or later the printing process or dirt brought in with the water used to extinguish the fires in the aftermath of the bombing of Dresden in 1945.

Figure 23: One of the historical books (nicknamed as 'SLUB groß') used for the first experiments. The image shows the full field of measurement in transversal slice orientation. The bright ring-like structure at the top is part of the fixation of the book inside the X-ray system. The very thin lines surrounding the book result from the plastic wrapping. © Fraunhofer EZRT

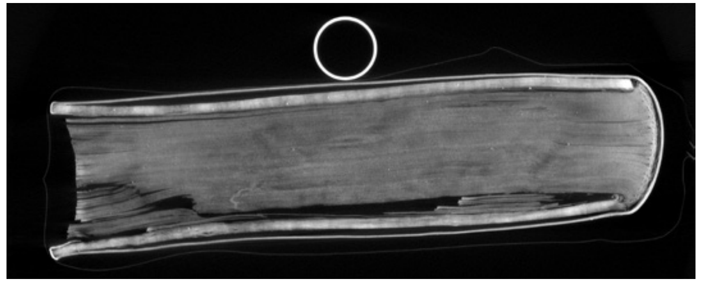
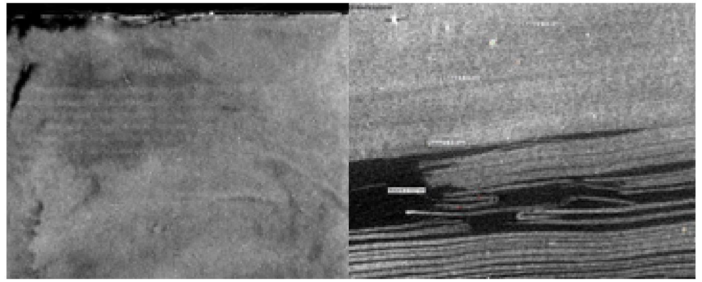


Figure 24: Two regions of interest in different orientations within the voxel volume. Left hand side from a book called 'SLUB klein' showing a part of the printed text. Right hand side from 'SLUB groß' showing regions where the single sheets of paper can be separated, whereas there are homogeneous regions too, which might indicate blocking. In addition, several highly absorbing, sand corn-like bright inclusions show up. Their true nature is not known up to now. © Fraunhofer EZRT



2.6 Possibilities of virtual reconstruction and assisted restoration

Johannes Hügle (Fraunhofer IPK),
Frank-Holm Rögner (Fraunhofer FEP)

Virtual reconstruction

After the interlocked fragments of books and writings have been separated, the documents can be reassembled. This first requires high-precision digitization. The scan module developed at Fraunhofer IPK together with MFB MusterFabrik Berlin GmbH offers the possibility of digitizing format-free flat objects on both sides. By using ultra-thin glass as a slide, this stripe scanner is also able to scan thick paper and paper that has been warped by water in a gentle and precise manner. Thanks to the transmitted light process used, paper structures and watermarks can also be made visible.

The scanner control software enables a double-sided and infinitely zoomable display of raw scans and pixel-exact digital copies. With the help of the software, the digital copies can be flexibly linked to meta information as soon as they are recorded. This can be done either interactively via the user interface or automatically by importing data that is available, for example, in an external data source for the inventory to be digitized. The digital copies are then linked to this data and passed on to reconstruction software.

The reconstruction software enables the automation of a wide range of reconstruction and reduction tasks. A wizard-based process allows the user to check the plausibility of the reconstruction and to manually "puzzle" fragment pairs together if there are insufficient features. The fragments are always virtually glued together in pairs to form a larger fragment, which is then reassembled with other fragments. In this way, the document grows step by step – even without knowing the target image or the completeness of the fragment set – up to an entire page, provided that all fragments are available.

Both the scanner and the reconstruction software are offered by MFB MusterFabrik Berlin GmbH and are already being used in a customer-specific implementation, e.g. for the reconstruction of the damaged documents in the historical archive of the city of Cologne.

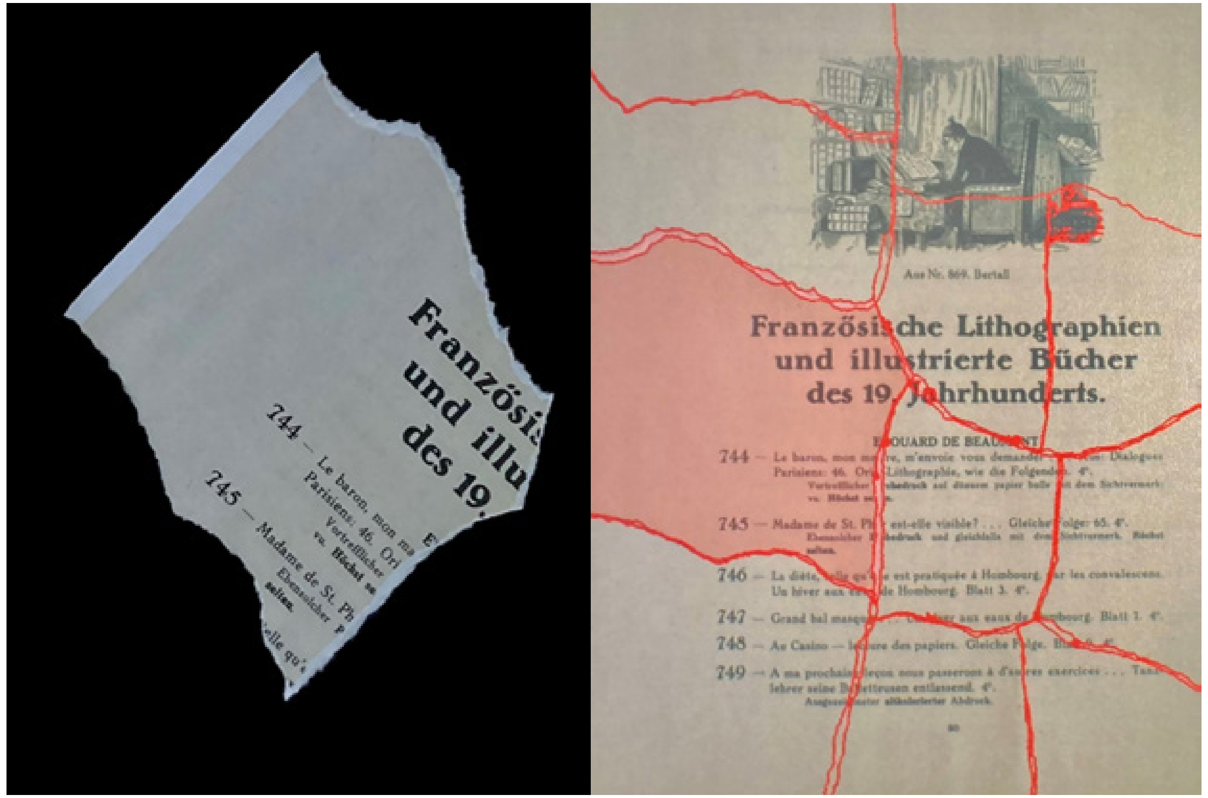
Assistance with the restoration

After the documents have been assembled virtually, a physical reconstruction can now be carried out. The scan data and the result of the virtual reconstruction are used to implement an assistance system for the real reconstruction. A calibrated setup with cameras and a projector that uses artificial intelligence methods enables this process to be accelerated. The projector projects the virtually assembled document as well as the edges of the fragments onto a table so that users are shown a kind of puzzle guide. If the user then places a fragment loosely under a camera with black background for the best contrast, it is automatically recognized and assigned to the corresponding virtual fragment with information about its position and orientation. The projected puzzle guide now highlights the corresponding location of the fragment in the document. The user can quickly find the target position and orientation of the fragment in the finished document. In the future it is conceivable that these individual fragments will then be connected automatically with the help of a robot. For this purpose, tests were carried out at the Fraunhofer IPK to determine to what extent the edges of the fragments can be recognized with sufficient sharpness and how precisely they can be approached automatically by a corresponding actuator.

In order to make the physical reconstruction after the digitally supported "puzzle" available for mass processing of archive materials through automated assembly and stabilization of the fragments, Fraunhofer FEP has been conducting research projects together with other partners for several years, with initial positive results in the field of fiber-reinforced light-curing polymers: (SMWA 2014-15, FKZ 100178078/2906; SMWA 2016-18, FKZ 100249563/3249; Patents: WO2021/255068, WO2021/255141, DE 10 2020 116 044 B3).

The latest investigations into the sensitive application of suitable monomer-oligomer mixtures were carried out as part of a diploma thesis at Fraunhofer FEP. Using an ink-jet printer a possible solution of spatially resolved application of stabilizing layers at the most fragile areas of paper based documents could be shown (Bredemeyer, 2022).

Figure 25: An exemplary fragment placed loosely under a camera (left) and the projection based on it on a white background with the target pose of the fragment highlighted in red (right) © Fraunhofer IPK



3. ENAMEL

Volker Franke, Florian Gruber (Fraunhofer IWS), Olaf Zywitzki (Fraunhofer FEP), Theobald Fuchs (Fraunhofer EZRT)

3.1 Motivation and objective

In February 1945 at the end of World War 2, a severe fire storm caused by bombing destroyed large parts of the city of Dresden. In this event also a truck laden with historical watches from the technical art collection burned down resulting in intense damage of these valuable objects. According to research of historians and object analysis, the damage was caused by estimated temperatures in the range of 600 to 800°C for several hours. Pocket watches from the 17th to 19th century are still part of the Staatliche Kunstsammlungen Dresden (SKD) collection but are not accessible to the public due to their impaired condition. Damage patterns are varying within a wide range including discoloring from grayish to black, cracks and melting effects. For the ornate enameled clock dials, there has been no suitable approach for restoration up to now. A first restoration study 20 years ago utilizing a cleaning laser based on nanosecond pulsed material ablation led to unsatisfactory results. It was possible to remove the damaged, dark top layer to unveil the unaltered enamel (see Figure 26). But the processed surfaces exhibited roughness values significantly increased by almost two orders of magnitude and thus unacceptable lackluster appearance. Objective of the FALKE project was the complete removing of the black surface layer without significant increase of surface roughness of the enamel by utilizing high precision ultrashort-pulsed laser ablation.

The research study pursued the following approach: At the beginning profound analysis of the damaged historic objects was conducted to determine the type and extent of materials modifications. Deduced from these results objectives and approach have been refined for the restoration of the objects. Cleaning experiments have not been possible on the historic originals due to their historic value and potential risk of unacceptable damage. Therefore, procedures were defined to fabricate prototype samples of similar material composition and damaging condition to be used for process development. Using an ultrashort-pulsed laser process development has been realized to ablate the damaged surface layer and thereby uncover the original unaltered enamel below. Repeated analyses were carried out for documentation and characterization of the resulting surface conditions regarding optical appearance (color, gloss), composition change and roughness.

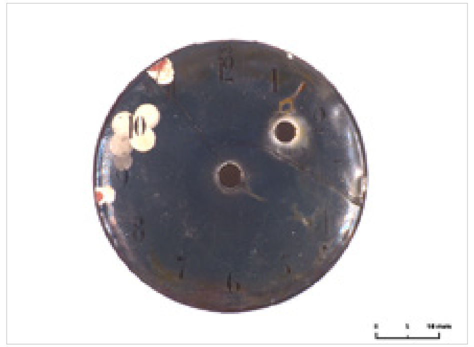


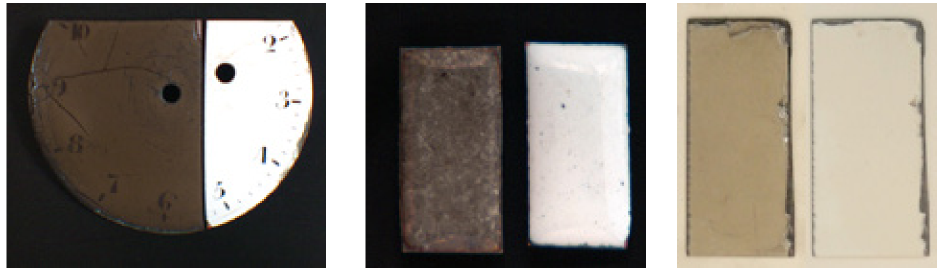
Figure 26: Fire damaged enamel dial of a pocket watch from SKD (inventory no. D IV a 450) with laser cleaned test spots © SKD

3.2 Preparation of prototype material samples

Three different types of sample material were used for the experimental part of the study on laser-based cleaning. The first material originated from a vintage promotional sign from the 20th century consisting of an enameled steel plate cut into pieces of ca. 100x100 mm^2. White and black surface sections of the enamel were available. Prior investigation the surface has been polished to remove layers of deposited pollution and unveil the bare enamel. This amply available material was primarily used for the basic research study on the interaction between the laser and enamel material. The second sample material was prepared by a restorer of the project partner SKD in the form of enameled copper pieces of approx. 10x20 mm^2. White enamel of a material mixture containing lead as being widely used in the 19th century has been applied. Thus, analogies to the material of the historic clock dials were anticipated. The third sample material was also provided by the SKD in the form of a contemporary clock dial from the time period of about 1800 in an undamaged original state.

All sample materials needed to be preconditioned to create a damage state comparable to the historic originals. According to the analysis results (see section 3.3), the material damages were targeted in form of a surface near chemical reduction. Thus, a heat treatment has been applied in a reducing atmosphere utilizing the following settings: temperature 600°C, atmosphere of carbon monoxide (60%) + argon (40%), duration 2 hours. As a result, especially the small lead containing samples and the contemporary clock dial showed a significant color change towards dark gray as can be seen in the picture below. The fact that the samples from the promotional sign showed comparably weak color change confirms that the dark appearance of the fire damaged clock dials is primary related to changes in the lead compounds of the materials.

Figure 27: Enamel sample materials prior (right) and after (left) heat treatment; from left to right: contemporary clock dial, enameled samples, segment of promotional sign
© Fraunhofer FEP, IWS

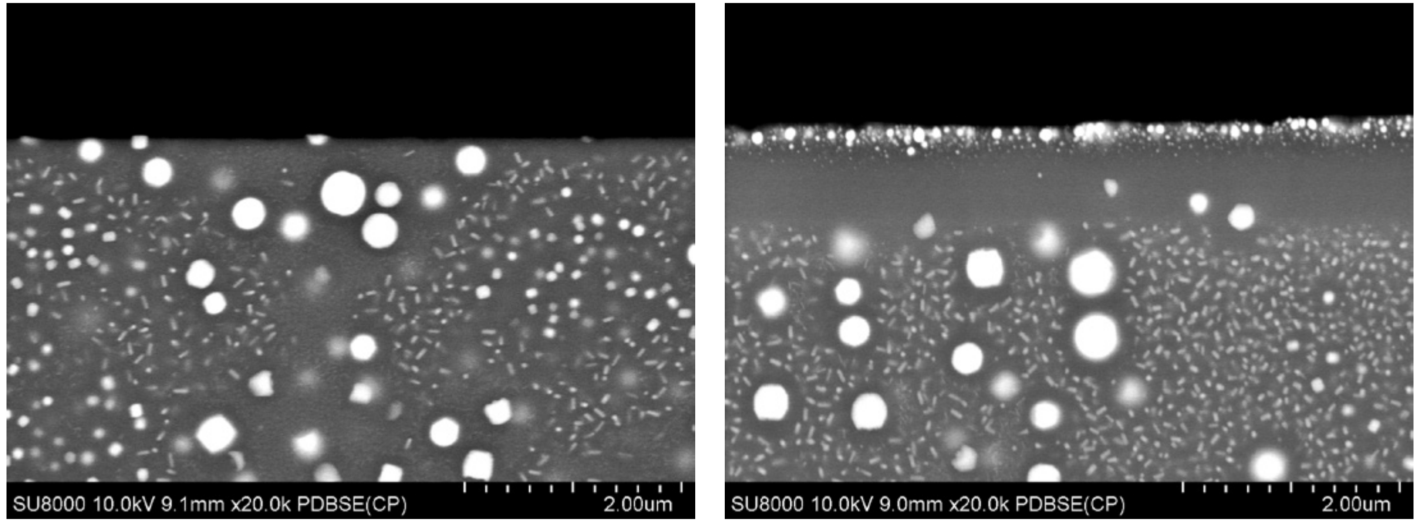


3.3 Analysis of historic originals and sample materials

The surface of the original fire damaged dial of a pocket watch (Figure 26) was analyzed by energy dispersive spectrometry (EDS) for chemical analyses of the vitreous enamel. The results reveal that the altered cover enamel contains about 31 wt.% SiO_2, 53 wt.% PbO, 11 wt.% SnO_2, 2 wt.% Na_2O, 1 wt.% K_2O, 1 wt.% CuO, 0.5 wt.% Al_2O_3, and 0.5 wt.% CaO. In spots where earlier laser ablation experiments removed the black surface layer, the PbO content is significantly reduced to about 20 wt.%, whereas SiO_2 is increased to about 50 wt.%. Simultaneously the surface roughness is increased significantly from arithmetic roughness value Ra = 0.025 µm up to Ra = 1.8 µm for maximum energy density of the laser cleaning.

On the contemporary clock dial the alteration of microstructure of enamel was investigated by field emission scanning electron microscope (FE-SEM) on ion-prepared cross sections. Results show that the initial state microstructure contains a homogenous distribution of 0.05 to 1.5 µm dispersoids of PbO and As_2O_3 in a SiO_2 matrix (Figure 28 left). After fire damage simulation a 1 µm thick structural altered surface layer is existing. The results of FE-SEM imaging and energy-dispersive X-ray spectroscopy (EDS) analyses show a 200 nm thin enrichment of PbO at surface. With increasing distance between 200 nm and 750 nm from surface the PbO content is decreased and SiO_2 content is increased. At a distance of about 1 µm the microstructure is comparable to the initial state before reducing heat treatments (Figure 28 right).

Figure 28: FE-SEM ion-prepared cross section of vitreous enamel from dial of a pocket watch before (left) and after heat treatment (right) under reducing atmosphere
© Fraunhofer FEP



The surface conditions of the investigated samples were also analyzed using hyperspectral imaging (HSI). Reflectance spectroscopy in the VNIR (visible and near-infrared, spectral range 400-1000 nm) and in the SWIR (spectral range 900-2300 nm), as well as the measurement of fluorescence after excitation with a 532 nm laser (spectral range 540-1000 nm) were used.

Figure 29 shows selected results of the HSI measurements of the fire damaged historic watch dial. Shown is the color-coded reflectivity at the indicated wavelength and some example spectra, the position of which is marked by colored crosses. It can be seen that HSI is suitable for a rapid and non-destructive determination of the actual condition of enamel samples. In particular, color differences can be detected with high accuracy in the VNIR measurements. SWIR HSI can also detect possibly hidden structures that are not visible to the naked eye.

A series of experiments has been conducted to find out, if the modifications as being seen in the FE-SEM images could also be recognized in high-resolution X-ray computed tomography scans. Different specimens were analyzed including a complete, functional modern pocket watch, an undamaged historical clock dial and two of the small, enameled samples (before and after heat treatment). The samples were examined with spatial resolutions of up

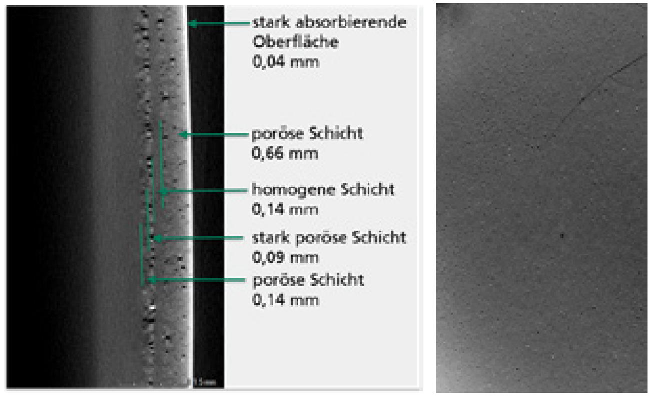


Figure 30: Small, enameled sample measured by 3D X-ray CT (spatial resolution 3.2 µm); transversal section through the probe (left), horizontal slice through the whole specimen (right) © Fraunhofer EZRT

to 3.2 µm. For all specimens there seems to be a highly absorbing thin layer on top of the enamel. A possibility that this thin white line is just caused by physical side-effects cannot be ruled out completely. On the other side, it might mark the white layer which contains highly absorbing lead pigments. Nevertheless, with this high-resolution scan no sub-structure inside the highly absorbing layer can be discriminated. Thus, the structural changes below the surface of the layer due to heat or fire occur on a smaller scale, probably in the sub-µm region. Also porosities and micro cracks inside the ceramic material are clearly visible independently from thermal damage conditions. Further experiments with an X-ray scattering approach are planned for the next future.

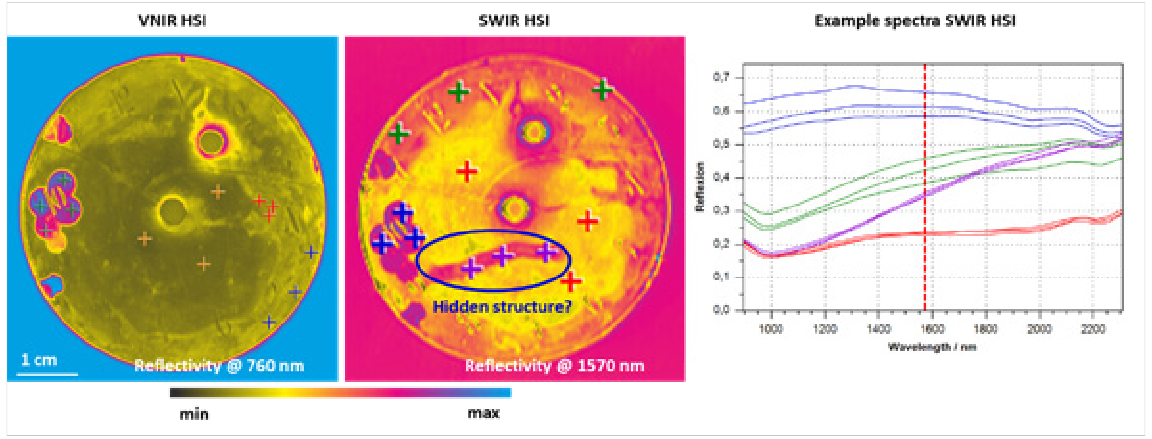


Figure 29:
HSI images of the fire damaged enamel dial of a pocket watch
© Fraunhofer IWS

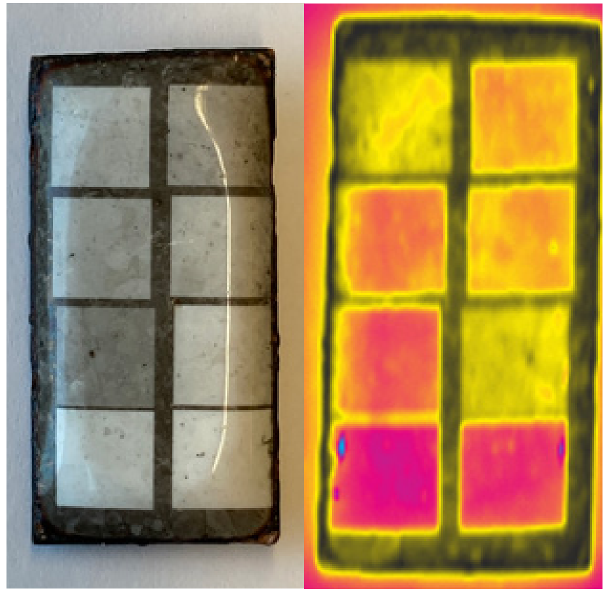
3.4 Laser cleaning of fire damaged enamel

Laser ablation processes were applied to gently remove the thin, dark film from the enamel. Therefore, a pulsed, intensive laser beam is focused onto the material causing instantaneous evaporation of a thin material layer. In contrast to well established laser cleaning by short laser pulses of several nanoseconds (10^{-9} s) ultra-short laser pulses of a few picoseconds (10^{-12} s) have been used. Depending on the material nanosecond lasers typically result in a thermally influenced layer of a few micrometers thickness including melt formation. Main advantage of the new approach with reduced pulse duration is that thermal damage to the base material can be avoided even in the micrometer scale. Within the time domain of few picoseconds no heat conduction takes place within the atomic lattice. Thus, the surrounding enamel is not thermally damaged or altered and processing precision is increased.

For the study, a laser system was utilized operating at an emission wavelength of 1064 nm, pulse duration 15 ps, adjustable pulse energy and pulse frequency. A galvanometer scanner dynamically deflects the focused laser beam (spot size approx. 55 µm) over the sample surface in a hatching motion to treat predefined areas. Due to the sample availability, fundamental experimental studies started on the samples from the enameled promotional sign before the findings were transferred to the small samples from the SKD and finally to the contemporary clock dial. Goal was to determine a process window wherein the dark surface layer is completely removed while preserving the low roughness value and thus gloss of the surface. The influence of main processing parameters on the resulting surface appearance has been investigated. Test areas up to 5 mm in size have been cleaned varying the following process parameters: laser pulse energy, pulse frequency, pulse overlap (pulse distance divided by spot size), hatching distance (respectively line overlap) and number of cleaning process cycles. The results were compared relating color change (brightening) and gloss (roughness).

The findings show that pulse energy is the decisive parameter. Once exceeding a material dependent threshold, material ablation starts resulting in visible brightening. The brightening effect increases with rising energy value due to increased material removal of the altered surface layer. Gloss and surface roughness are not affected by the pulse energy level within a given process window (approx. between 1.5 µJ and 9 µJ) being material dependent. Within this parameter field the measured surface roughness was even reduced from approx. R_a 0.17 µm, R_t 1.6 µm (heat treated enamel) to approx. R_a 0.10 µm, R_t 0.9 µm (after laser cleaning). At even higher pulse energy the gloss of the enamel is visibly reduced due to increased material removal. For the utilized experimental setup pulse frequency, pulse overlap, and number of processing cycles have only minor influence on the cleaning result but mainly on the processing speed. Figure 31 shows an enameled test sample with laser cleaned areas using different settings illustrating that the cleaning effect can be controlled purposefully by varying process parameters. HSI analyses are a valuable method to automatically quantify the laser cleaning results.

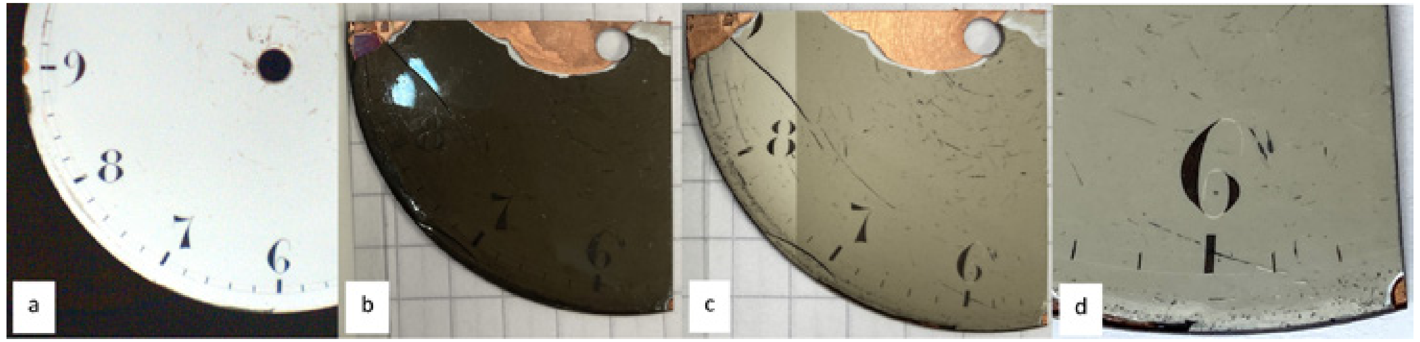
Figure 31: Laser cleaning experiments on small, enameled sample with varying laser process parameters, true color image (left) and VNIR HSI image reflectivity @ 600 nm (right) © Fraunhofer IWS



To demonstrate the results of this research study on a real historic object finally the laser cleaning process has been applied to the thermally treated contemporary clock dial segment. The complete surface was cleaned homogenously using a pulse energy of 6.2 µJ resulting in a visible brightening. On the left-hand side one portion of the surface was additionally treated at an increased pulse energy of 9 µJ exhibiting an even brighter appearance but slightly reduced gloss of the surface. A complete reversion of the material modifications was not achieved. Optical microscopy revealed that material of the printed inscriptions is partly ablated slightly reducing their visibility. This unwanted effect can be avoided by spatially selective processing of the surface (only irradiating areas of uniform material, e.g. leaving out printed inscription) in the future.

Summarizing the investigations on laser cleaning of fire damaged enamel: it was shown that ultrashort-pulsed lasers achieve superior results compared to state-of-the-art nanosecond laser cleaning systems. Ongoing development work needs to focus on process control and strategy to precisely treat objects spatially selective depending on their individual surface condition. Against the background of climate change and growing risk of fire events the results present a promising restoration approach not only for historical objects which are already subject of fire damage.

Figure 32: Contemporary clock dial, before (a) and after (b) heat treatment, after ultrashort-pulsed laser cleaning (c, d), magnified detail with partly ablated inscription (d) © Fraunhofer FEP, IWS



4. NEW INVESTIGATIONS OF THE "ASTERIXE" AT THE OUTDOOR TEST SITE IN HOLZKIRCHEN

Kristina Holl, Martin Krus, Timo Hevesi-Toth, Stefan Bichlmair, Ralf Kilian (Fraunhofer IBP)

4.1 Introduction

Our cultural heritage is constantly threatened by anthropogenic phenomena. Today we are mainly concerned by the impact of climate change. 30 years ago, the acid rain was the most challenging cause for damages to monuments. Besides the forests, especially stones and glasses were affected by sulfur dioxide or high NO_x concentrations in the atmosphere. From 1986 to 1996 the BMFT (Federal Ministry for Research and Technology) conducted a national funded project on the research of stone decay on built heritage. The focus was on the examination of stone weathering phenomena in Germany. During that time many test sample fields were installed all over Germany (Brüggerhoff, 1989). Duisburg and Holzkirchen were selected as outdoor research areas for the so-called "Asterixe", large exposure blocks with a unique design. The indications for regional and localized weathering trends would aid managers in understanding risks and setting priorities – both for further monitoring and for conservation interventions.

To simulate typical surfaces of historic monuments the stones were shaped with typical geometric forms such as slopes, cornices or surface treatments (carving) which are considered crucial to examine the interaction of the surface and the environmental weathering effects, see Figures 33 and 34. As the changes and damage processes differ depending on the variety of rocks and their types of binding (siliceous, carbonaceous, clayey, pure lime, etc.), seven different stone types commonly used in historic buildings and monuments have been chosen for outdoor exposure. Today, most of the test sites in Germany were removed, but in Holzkirchen most of the samples are still at their original position. The combination of a long-term climate measurement on site and the natural exposure of the stones is a unique and valuable treasure for scientific investigation. Future research topics include the effect of climate change on natural stones or the examination of protective housings for outdoor sculptures.

4.2 Past research on stone deterioration on the "Asterixe"

During the time of the BMFT project, numerous measurements have been carried out. Besides measurements to determine material criteria (water vapor diffusion resistance, water uptake, hygric strain, etc.) the change in weight, roughness as well as biological growth has been examined. The state of preservation was documented regularly to show optical and physical changes caused by the weathering as well as the effect of salt, different consolidants or hydrophobization. During that time climate measurements have been established. They served as a baseline for the comparison of the effects at each test site – in Holzkirchen as well as in Duisburg.

After the first years of exposure of the "Asterixe" typical damages, such as cracks, material losses, dust, discoloration, or blooming were found and categorized on the stone samples, see Figure 34 right. The effects of the two different sites Duisburg (industrial site) and Holzkirchen (high rate of freeze-thaw changes and clean air) were compared (Sasse, 1996). Especially the Ihrlersteiner Green-

Figure 33: Original set up of the „Asterixe" in Holzkirchen in Bavaria, December 2010 © K. Holl, Fraunhofer IBP

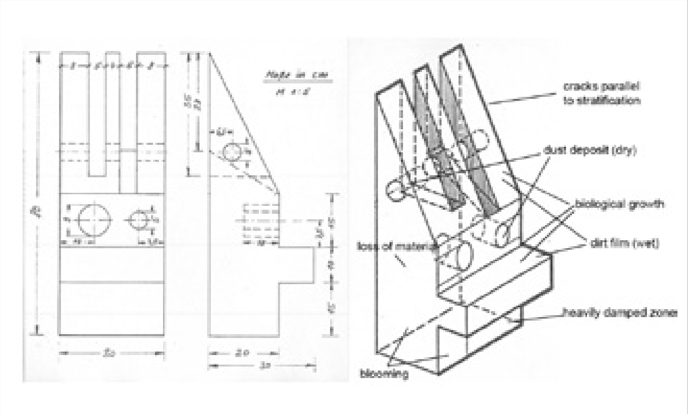


Figure 34 left: technical drawing of an "Asterix" with dimensions indication © Fraunhofer IBP, ca. 1986. Right: overview of typical damages on the "Asterixe" after the first two years of exposure © Fraunhofer IBP after Brüggerhoff, 1989

sandstone and the Sander Sandstone were used for detailed examinations, such as cleaning, hydrophobizing and the application of two different kinds of consolidation material in 1995. Before and after the treatments examinations of color change and ultrasound have been carried out (Krus, 1995).

As a first conclusion it was stated that the stone decay is a complex problem. For the examination of stone decay which is strongly dependent on the individual material properties, it is necessary to have original test samples which are exposed on site as a base for interdisciplinary research.

4.3 Reviving the "Asterixe"

Currently, the original "Asterixe" stone samples are used for the investigation of the effects of climate change on built heritage and archeological findings (Daly, 2019). After more than 30 years of outdoor exposure, the stone collection in Holzkirchen is now receiving new attention (Wilhelm et al., 2020). Within the frame of the Research Alliance Cultural Heritage, the "Asterixe" have been investigated with different techniques. The idea was to use state-of-the-art techniques to generate data of the stone samples as a new baseline for future research. Four stones – Sander Sandstone and Ihrlersteiner Greensandstone from Holzkirchen and Duisburg – have been selected for exemplary measurements, see Table 1. So far, the stones have been scanned with an XXL computer tomography at the Fraunhofer EZRT in Fürth (see Figure 35). In XXL CT, large objects are recorded and examined three-dimensionally with high X-ray energy (9 MeV). Depending on the investigation task, spatial resolutions of about 200 µm are achieved. Therefore, this technique was used to digitize four "Asterixe" in three dimensions.

In cooperation with the University of Bamberg 3D scans of the four stones have been carried out using the method of structured light scanning with a T-Scan from Steinbichler (now Zeiss), see Figure 36. The change of the stone samples, for example the degree of weathering due to the change in climate can now be detected and quantified by the comparison of the 3D scans in accordance with the measured climate data.

The change in weight is a precise information for the water uptake of a stone. It can be used among others to validate simulated data. Therefore, an automatized balance was developed and installed to measure continuously the weight of one of the weathered "Asterixe" (Sander Sandstone VI-1). Figure 37 shows the weight depending on the current weather data (temperature, solar radiation, relative and absolute humidity, wind and rain) from March to May 2022.

Identification	Stone	Position	Description	Measurement
II-8	Ihrlersteiner Greensandstone	Holzkirchen since 1986	untreated	3D scanning, XXL-CT
VI-3	Sander Sandstone	Holzkirchen since 1987	untreated	3D scanning, XXL-CT
VI-6	Sander Sandstone	Holzkirchen since 1987	cleaning, hydrophobizing and application of consolidation material in 1995, examination of color change and ultrasound before and after treatments	3D scanning, XXL-CT
VI-7a	Sander Sandstone	Duisburg installed in 1987, since 2010 in Holzkirchen (storage)	untreated	3D scanning, XXL-CT
VI-1	Sander Sandstone	Holzkirchen since 1987	untreated	weight changes

Table 1: Listing of the selected stones for further research (3D scanning, XXL-CT, terahertz, ultrasound, 3D microscopy)

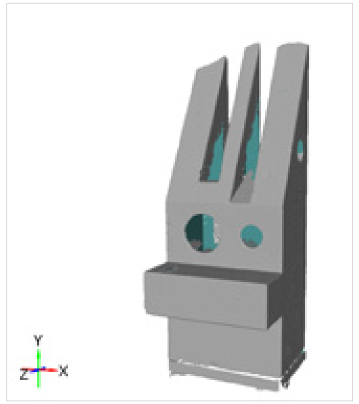


Figure 36: Screenshot of the point cloud of the 3D Scan from "Asterix" IV-3 (Sander Sandstone) © L. Pallas, University of Bamberg

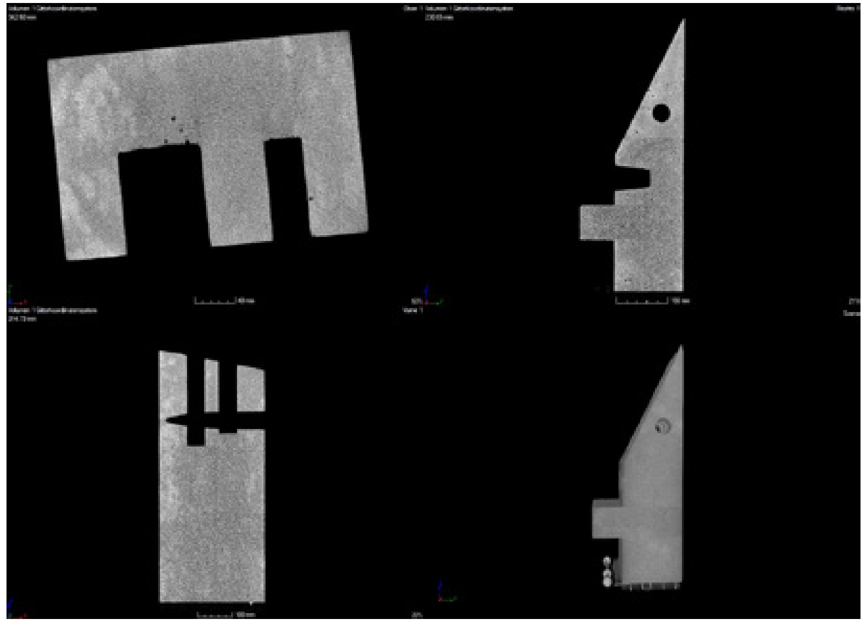
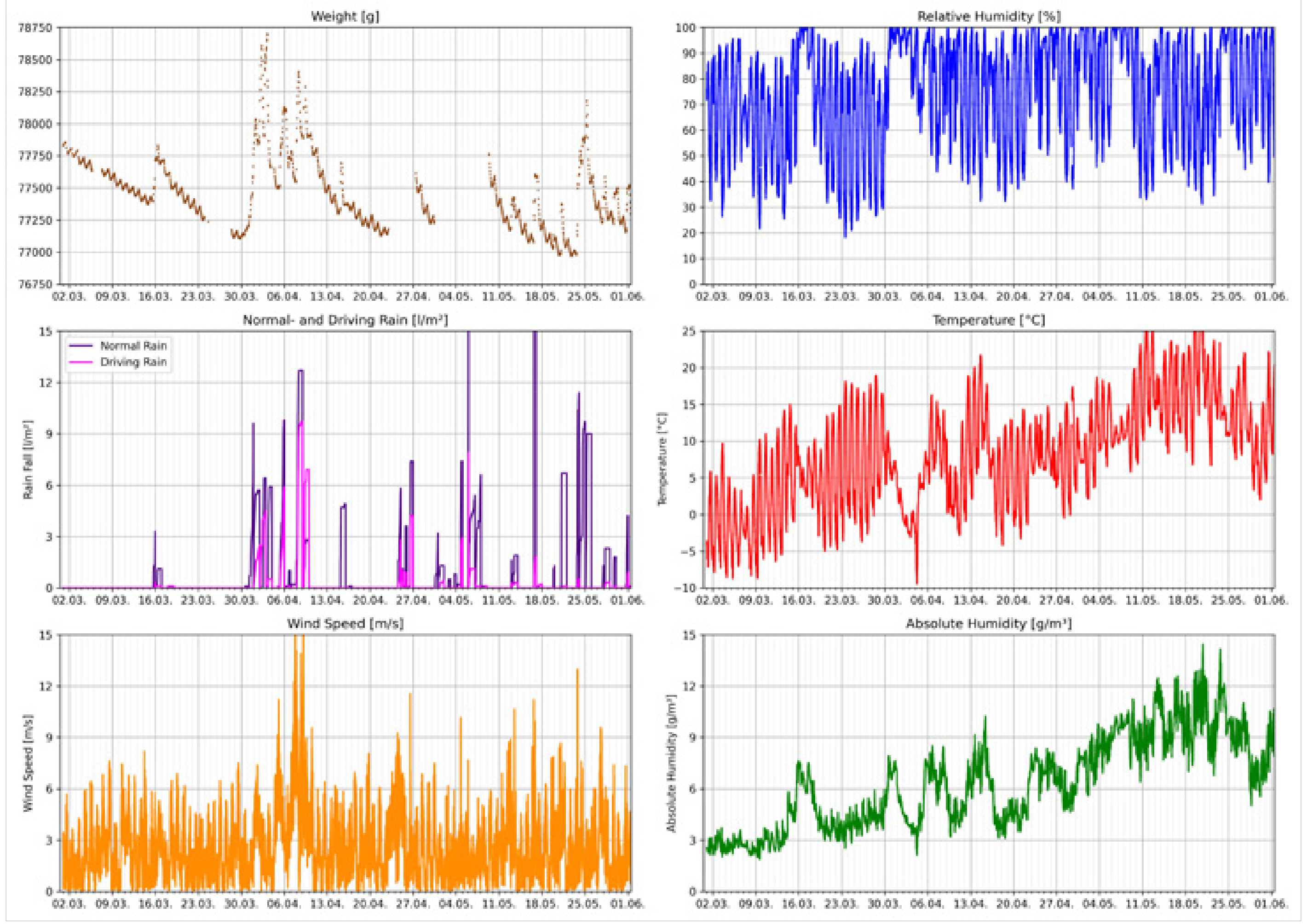


Figure 35: Computer tomography of "Asterix" II-8 (Ihrlersteiner Greensandstone) © M. Böhnel, Fraunhofer EZRT

Figure 37: Climate data from the weather station in Holzkirchen in comparison with the weight of the "Asterix" VI-1 (Sander sandstone) from March 2nd to May 11th 2022
© T. Hevesi-Toth, Fraunhofer IBP



4.4 Outlook

Within the scope of the current project, further measurements with ultrasound, terahertz, and confocal microscopy as well as a hygrothermal simulation of one "Asterix" with past and future climate data will be executed. All available historic data on the "Asterixe" experiments will be further sifted, digitized and sorted. All information (e.g. from the project Stone Decay, as well as the documentation of the original locations, changes of location, historical photographs, etc.) will be stored in a database in which the digital data for each individual "Asterix" will be located, with the final goal of developing digital twins which can be monitored further in the future to learn about deterioration mechanisms and the influence of climate change. Furthermore, information on historical monuments (sculptures, façade parts, gravestones, etc.) will be indexed and selected for each stone.

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CHAPTER 4

VALUE OF CULTURAL HERITAGE AND VISITOR PREFERENCES

VALUE OF CULTURAL HERITAGE AND VISITOR PREFERENCES

Uta Pollmer, Erik Schmidt (Fraunhofer IMW)

Cultural heritage plays an important role in our lives. It is of economic, social, cultural, and environmental importance to our society. The impact of cultural heritage and its preservation has already been investigated in many studies, especially in the economic area. Against the background of justifying investments, safeguarding cultural heritage has been recognized as "… a 'multiplier' through which investment can have positive impacts …, thereby increasing the level of benefit and sustainability of the initial investment." (Jagodzińska et al., 16-17) But what exactly are the benefits of protecting heritage? How can its specific value be determined? And how do emergent and established trends of digitalization play a role in the value and valuation of cultural heritage?

In this chapter, we introduce two methods to determine the use and non-use values of cultural heritage, investigate the value of original cultural assets and the benefits of digitization, and present a method to prioritize the implementation of digital offers in heritage institutions. The section on the benefits of digitization and the value of originals structures existing concepts in the literature. Then the methods are briefly summarized and case studies are used to present possible applications.

1. USE AND NON-USE VALUES OF CULTURAL HERITAGE

Our market driven society tends to express values in monetary terms like euros or dollars, because the market price of an object makes it possible to compare its value with that of other objects and – in the case of cultural assets – justifies investment in their preservation. Certain cultural assets are, of course, traded on the market. But in the case of museums, libraries or archives, historic parks and gardens we mostly talk about non-market goods: It is difficult to define their value by setting a price. Mourato et al. (2014, 15) state that cultural assets are "… usually publicly owned and freely accessible ..., [and if there are access fees they] are usually nominal and not related to the true cost of providing and maintaining them." This challenge is typical for non-market goods and has been addressed in the heritage field since the 1980s (Mourato et al., 2014). Many studies have followed the principles of environmental economics, where the Total Economic Value (TEV) (Krutilla, 1967; Randall, 1987) is used to describe and assess ecosystems and their services by integrating market and non-market values. Similar to ecosystem services, individual benefits or values with influence on human well-being can also be defined for the field of cultural heritage.

The TEV differentiates between use and non-use values, where use values arise from the use of an object, and non-use values are associated with an object even when it is not used (see Figure 1). The following use values have been identified for cultural ecosystem services and can also be associated with the use of cultural heritage, e.g. with visiting a museum or historic garden: recreation, aesthetics, spiritual enrichment, ethical requirements, cultural identity, a sense of place, knowledge and cognition (Natural Capital Germany – TEEB DE, 2018). These values are not fixed but can be structured differently depending on the focus of the investigation. For example, according to Throsby and Zednik (2014, 84), the cultural value of art assets consists of the aesthetic, social, symbolic, spiritual and educational value of an object. Non-use values include the option value (potential future use), the existence value (value of an object without using it), the altruistic value (knowing others using it) and the bequest value (preservation for future generations). The option value is sometimes seen as a future use value and therefore assigned to the use values by some authors.

Use and non-use values can be measured via different indicators and methods. According to the literature, preference-based methods have been identified as the most appropriate to valuate cultural heritage (Mourato et al., 2014). The most frequently used methods here are the contingent valuation method and the travel cost method.

1.1 Contingent valuation method

The contingent valuation method (CVM) is one of the methods of stated preferences that can be used to evaluate non-market assets and to capture the non-use values of an object. Therefore, the respondents are presented with a real or hypothetical scenario and asked for their individual willingness to pay for preserving or improving the described status. A scenario could be, for example, the current (conservation) status of a collection, or specific visitor services. Alternatively, the willingness to accept a worsening of a scenario or the degradation of a heritage asset or collection can also be queried – related to a compensation for the loss. Both reflect the individual appreciation for an object or scenario and are used to determine its value.

The CVM is used to investigate non-use values, when non-visitors and people who do not even know the object of investigation are to be addressed. Depending on the sample and the topic, use values and visitors can also be considered. Moreover, the hypothetical design of the scenario allows future developments to be included in the assessment, although distortions can be expected with a hypothetical query. When evaluating such surveys, a certain degree of uncertainty about the reliability of the information must be taken into account, which arises from difficulties in translating immaterial benefits into monetary value (problem of abstraction), from having limited information about the scenario, a lack of incentives to carefully consider the correct answers, and from "free rider behavior" (providing incorrect answers for strategic reasons).

Caution is particularly important when dealing with the amounts of money chosen by the respondents. Concerning the value of art assets, Ginsburgh and Throsby (2014, 3) stated in the Handbook of Economics of Art and Culture: "In conventional economics, a consumer whose demand for, say, a work of art is motivated by his or her perceptions of its aesthetic or symbolic qualities will express the strength of those perceptions in his or her willingness to pay

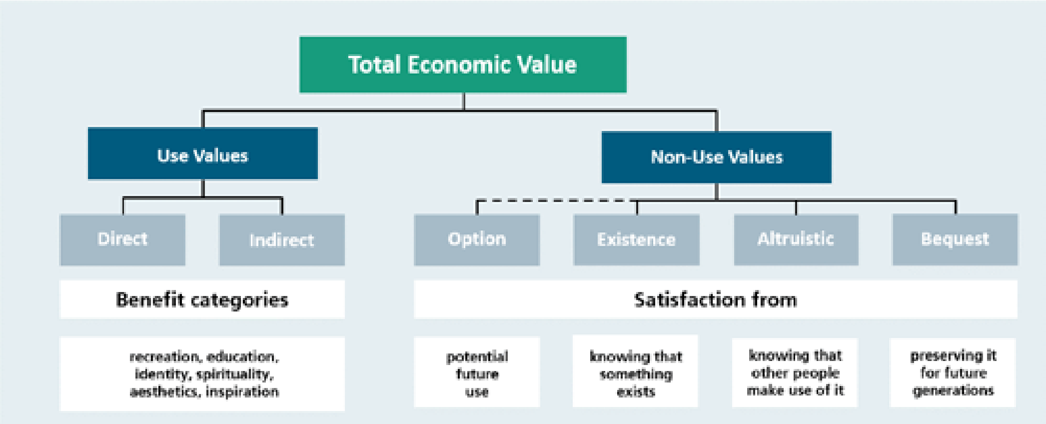


Figure 1: The total economic value of cultural heritage. Own figure based on Naturkapital Deutschland – TEEB DE (2012)

Figure 3:
UNESCO World Heritage Site Pompeii
© Uta Pollmer

for the work." This works well for the art market, but for public museums, collections and historic gardens, we see the willingness to pay as a means to make non-priceable benefit aspects visible, to show the people's appreciation for cultural heritage, and last but not least as an indicator to investigate the weighting of the various use and non-use values as explained below.

We applied the CVM in two case studies, each in a representative population survey for Germany (online) with 1,000 respondents: 2018 for the Ethnological Museum in Herrnhut and 2020 for the UNESCO World Heritage Site Pompeii. The scenario chosen for Herrnhut was the preservation of the current state, for Pompeii the support of a summer academy for restorers to preserve endangered objects. Among other things, respondents were asked about their willingness to pay and the reasons for their decision. The relevance of the influencing factors was determined using a linear regression analysis, i.e., the evaluation of the statistical relation between the stated reasons or other factors and the willingness to pay. Normally, the motivation is a combination of several reasons, which the respondents are often not aware of, but its weighting can be statistically proven in the response behavior. In addition, the statistical evaluation can also include factors that are not listed directly as answer options (attitudes, socio-demographic data, etc.).

Compared to a simple query of the reasons, the CVM is therefore more precise in classifying the answers. In the Pompeii case study, a comparison was also drawn between the relevance of use and non-use values. The study showed that both the willingness to pay per se (> 0 €) and the amount of money people are willing to pay are significantly more influenced by the perception of non-use values than by use values or demographic factors such as income or education.

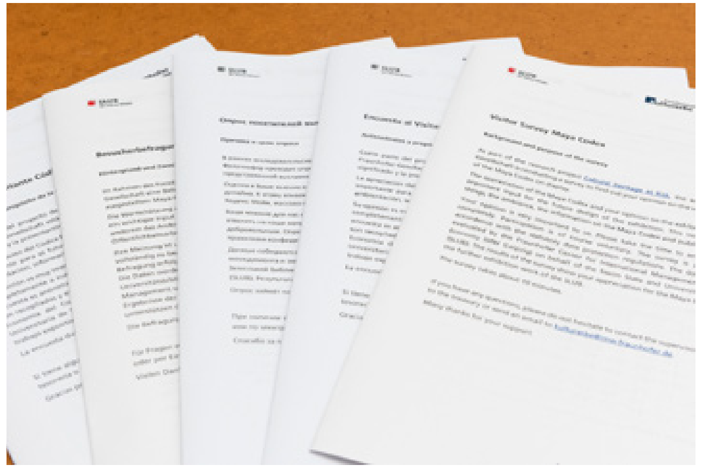
Figure 2:
Ethnological Museum of Herrnhut
©Atelier Schmorrde, Herrnhut

1.2 Travel cost method

The travel cost method (TCM) is especially suitable for the estimation of use values. It belongs to the methods of revealed preferences and measures the effort that visitors make to visit a cultural asset. To calculate the use value, data on real costs for a visit is collected, and the total amount is taken as the minimum individual benefit recognized by the visitor and thus as the minimum, which he or she is willing to pay. In addition to direct costs in the form of travel costs and admission fees, real costs also include opportunity costs for the amount of time spent for the journey and the visit itself.

Based on information about visit frequency, real costs, and visitors' motivation, a demand function can be created by using a linear regression analysis. The demand function not only provides information on the maximum willingness to pay (reflecting the benefit of a museum visit to the visitor), but also on the consumption behavior of visitors in the case of fictitiously increasing costs from which the consumer surplus can be derived. The consumer surplus describes the difference between this benefit and the real costs that visitors incur in order to enjoy a certain good, taking into account a decrease in the frequency of visits in the case of rising costs. Accordingly, the consumer surplus is the amount of money that visitors do not have to spend even though visiting the museum would be worth it to them. That means, the consumer surplus represents an economic benefit and can be regarded as a partial economic value of a heritage site. Therefore, it can be used as an argumentation aid and basis for investment decisions.

Figure 4 and 5: Maya Codex survey at the treasury of SLUB started in April 2022
© SLUB



The advantage of the TCM is that the results are based on actual behavior using robust statistical methods and thus reflect the real (minimum) amount a visitor is willing to pay. Moreover, it is applicable to all types of cultural heritage. By using proxy markets (tourism, transport, hotel industry, labor market, etc.), data about the costs paid are relatively easy to collect. However, the costs are strongly influenced by external circumstances such as fixed admission prices or the distance of the heritage site from the place of residence. The calculation of the opportunity costs on the basis of time spent and individual hourly wage is a bit more complicated. The answers given by respondents are sometimes subject to strategic considerations or prone to social desirability bias.

The exact distribution of costs across various cultural assets is also difficult to determine, if several destinations are associated with the same costs. In this case, the respondents are asked to weight the object of investigation against other travel destinations, e.g. as only destination, main destination, one of several equally important destinations, or as a secondary destination. The specified weighting of e.g. 100%, 80%, 50% or 20% is then multiplied by the travel costs incurred, so that only the relevant part of the travel costs is included in the calculation of use value.

We applied the TCM in our 2022 case study for the Maya Codex exhibited in the Treasury of the Saxon State and University Library Dresden (SLUB). After 3 months, a first evaluation by TCM, based on 45 questionnaires, demonstrated that the visitors can be divided into two groups that differ in their motivation and willingness to pay. While for the first group the Maya Codex played only a minor role during their trip to Dresden, we were able to identify a larger group of visitors for whom the Maya Codex was the sole or main purpose of their trip. This group consists of people from all over the world, especially from Mexico, Colombia, Guatemala, and the USA, who come to Dresden in order to see the Maya Codex. They usually have an intrinsic, spiritual, or scientific interest in the Maya Codex and are accordingly willing to accept very high costs to see the Maya Codex.

Compared to other studies in this field, the individual consumer surplus for the Maya Codex visitors is relatively high. In this context, the results of the TCM reflect the high international relevance of the Maya Codex due to its high cultural and spiritual value and emphasize the value that visitors attribute to the Maya Codex and its preservation. In studies like this, the TCM provides museums and other institutions with key insights into the motivation, background, and willingness to pay of their visitors. The visitor survey in Dresden will be continued and regularly evaluated in order to obtain valid results with an increasing number of respondents.

2.1 Benefits of digitization

Digitization has become an integral part of many areas of our lives. And digital technologies are also being used more and more in the cultural heritage sector. In particular, the Covid-19 pandemic has led to an increased use of digital media in the cultural sector in general and to "a renewed engagement and interest from local communities and domestic tourists" (ICOMOS, 2020, 16). Against the background of the worldwide closure of heritage sites, ICOMOS reports in 2020 (p. 21) on a "significant increase in the use of digital technologies and social media for virtual exhibitions, webinars, and courses related to heritage sites" in several countries. The NEMO report of 2021 approved this trend particularly for museums. The ICOMOS report (2020, 21) states further: "Digital technologies significantly contributed to the accessibility, use, and enjoyment of tangible heritage, as much as the wider engagement from local communities, …".

But how do digital technologies support the cultural heritage sector? What benefits arise from the digitization of cultural heritage? The ICOMOS report already indicated some benefits. According to our literature review, and considering the available technologies, benefits of the digitization of heritage assets are most likely to be found in the following fields: documentation, preservation, research, transfer, marketing, and democratization (see Figure 6).

Figure 6: Benefits of digitization of cultural heritage assets, own figure based on literature review © Fraunhofer IMW

Documentation	Preservation	Research	Transfer	Marketing	Democratization
Data collection	**Protection**	**Semantic links**	**Cultural education**	**Incentives**	**Accessibility**
making the hidden and invisible visible	using digital twins for research or exhibitions	linking open data, making new data accessible to research	providing access to new environments and contexts	publicity through social media, increasing attractiveness by digital offers	creating barrier-free, time and space-independent use of online formats
Monitoring	**Prevention**	**Data analysis**	**Visitor engagement**	**New target groups**	**Participation**
collecting and processing real-time data	simulating damage or processes of ageing, reducing costs	evaluating larger data volumes faster, detecting deterioration factors	providing immersive experience	providing digital offers for specific audiences	creating prosumer transparency
Data storage	**Restoration**	**Cooperation**	**Visitor understanding**	**Merchandise**	**Empowerment**
improving accessibility, availability	refining restoration techniques	providing exchange platforms	digitalizing the implementation of narratives	improving/creating online shops, 3D prints and digitized products for sale	opening up institutional barriers

In the fields of cultural heritage documentation, preservation and research, digitization and digital technologies offer unprecedented opportunities to generate new data and insights. Several digital technologies like X-ray, ultrasound or terahertz, allow to investigate subsurface damages or changes that would be almost impossible to detect manually or by analog means without damaging the material (Zerbe, 2020). The collection and processing of real-time data, the calculation of decay factors, the simulation of damage and ageing processes, etc. can support the decision process for appropriate preservation strategies and activities, including prevention and restoration. Timely intervention, targeted measures and improved techniques have further effects, such as preventing damage and reducing costs.
The digitization of objects, the linking of data and the creation of digital twins (see chapter 2 in this volume) are of particular benefit for research as well as for education, outreach and marketing. In addition to gaining scientific knowledge, digital technologies such as virtual or augmented reality can provide visitors with access to entirely new spaces and contexts (Ceynowa, 2015). They offer new incentives for a visit and are suitable for addressing new user groups. Cultural education can take place anywhere and anytime. Digital Twins enable the production of detailed facsimiles, which can be used as additional or in some cases as alternative exhibition objects to avoid originals being exposed to disadvantageous conditions. At the same time, digital technologies allow new forms of interaction. Furthermore, the past can be brought back to life: objects that are barely preserved or only have their fragments left can be experienced in their entirety through digital reconstruction and 3D models (Haas, 2018).
Digital platforms, archives, and databases have revolutionized research by connecting knowledge, digitized collections, and exhibits of a wide range of institutions (Gramlich, 2017). This has not only facilitated research and the search for specific exhibits, but also enables entirely new semantic links between different institutions and their inventories beyond temporal and spatial limits (Kind, 2021). In addition, the use of algorithms makes it possible to analyze data volumes of unimagined size and speed. Social platforms specifically dedicated to researchers and practitioners in the cultural heritage field contribute to international and interdisciplinary networking, cooperation, and exchange between different actors and institutions.
In the field of knowledge transfer, digitization is opening up entirely new avenues. Cultural education can now take place anywhere with digital content; and it can access entirely new spaces and contexts (Ceynowa, 2015-2). School classes no longer necessarily have to travel to a museum, they can also take part in virtual tours via the internet if the museum in question is too far away, for example. Through social media and websites, museums and other institutions have new ways to draw attention to themselves, their work and exhibitions empowering smaller institutions in comparison to established and internationally popular museums (Niewerth, 2018). The internet provides museums with the opportunity to present objects beyond their physical exhibition, to develop different offers and content for different user groups, and to attract new audiences. According to Niewerth (2018), virtual exhibitions can refer to the physical exhibition in the museum in different ways. The virtual exhibition may function as an extension of the exhibition, as a reference to it, or as its duplicate.
Last but not least, digitization has the potential to contribute to the democratization of the art and cultural heritage sector. Online formats per se have a high level of accessibility, but physical exhibitions can also be made more inclusive by means of digital technologies and adapted to the needs of people with disabilities, for example (Zinnatova et al., 2018; Dobroschke & Kahlisch, 2019). Furthermore, visitors can be involved in specific work and decision-making processes via online participation formats. There is an increasing demand and willingness of visitors and interested laypeople to participate in decisions about exhibition objects and topics as well as preservation and documentation work, and to contribute to knowledge and content production, which is why Pöllmann and Hermann (2019) call such visitors and laypeople "prosumer". According to Ferri et al. (2020), "Heritage Social Platforms" can also raise awareness, establish an active community, bring cultural heritage into people's daily life, make heritage more accessible and dynamic, involve civil society in heritage preservation and thus contribute to break up institutional barriers.

2.2 Value of original heritage assets

The methods described at the beginning of this chapter are used to illustrate the value of cultural heritage and the importance of its preservation. But in the age of digitization, when digital twins can be created containing lots of data about the inside and outside of an object, the discussion about the preservation of original assets plays an increasingly important role. Why should we preserve the original, if we have access to the digital twin and all related data anytime and anywhere?

The value of original cultural heritage assets is inseparably bound with the value of the museum and other public cultural institutions as the specific places where the original is presented, preserved, and publicly accessible. Even though the original bears an exclusive character being presented in the museum, it still remains the only place for most people, where they can immediately experience original art and cultural heritage. Therefore, the original and its values cannot be adequately understood without also keeping the place in mind, where it is presented and can be experienced. So, when we ask ourselves against the backdrop of digitalization: Why should we preserve the original?, we should also ask: Why should someone still want to go to the museums if he or she can go online, participate in virtual tours through the same digitalized exhibition and see perfect digital twins of the originals instead? The following part of the chapter seeks to answer both of those questions.

What is the specific value of originals? According to our literature analysis, the benefits that make up the value of an original can be classified into the following categories: the aura of the original, individual benefits for the user, research benefits, and social benefits.

Figure 7: Benefits of preserving original cultural heritage assets, own figure based on literature review © Fraunhofer IMW

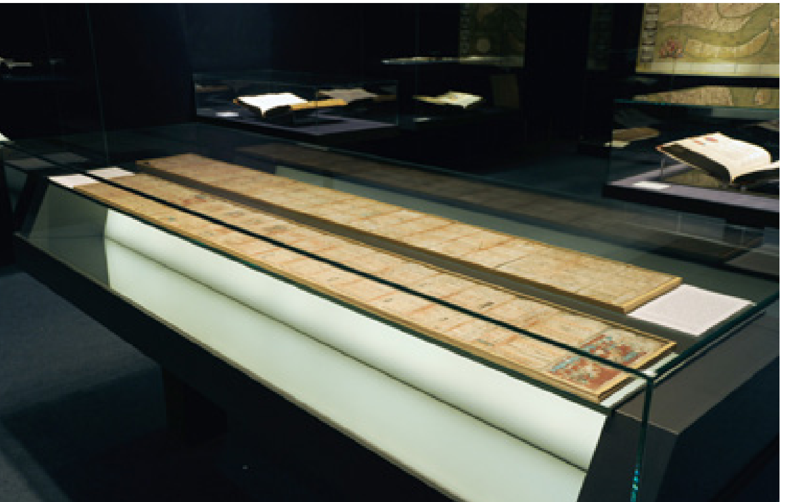
Aura of the original	Individual benefits	Research benefits	Social benefits
original as a witness of history and a carrier of historical significance	unique experience: special effect of the original on its spectator	original as infinite and unlimited research object	museum as a contact zone for social groups
authenticity and unique materiality of the original	museum as a place of learning	museum as a place for lived experience and transparency of research and preservation work	museum as a place of subversion and contradictory narratives
high social prestige of an original	original as a source of inspiration	museum as a creative open space for research and culture	museum as a place of remembrance and identity creation
exclusivity related to visiting the original	spatial experience in a museum	original as a source for fundamental research about provenance	original as an object of spiritual practices and rituals

According to Benjamin (1963), exclusive access is one of the main features that gives the original object its mysterious aura, which distinguishes it from copies, facsimiles, and other replicas. 'Exclusive' here means that the original presented in a specific place is excluded from our daily experience (Berger, 1990). The original is further characterized by its historic origin, its authenticity and unique materiality (Hampp & Schwan, 2014). It is a witness of time (Korff et al., 2007), history can be explored and researched through the engagement with the original object. Memories, emotions and narratives are associated with it. Its authenticity derives from its unique materiality, marked by time and signs of ageing, telling stories about the past. This aura will be always missing "even in the most perfect reproduction" (Benjamin & Zohn, 2018, 7).
Specifying the use values for visitors, some researchers state that because of its aura, the original evokes a special effect on its spectators (Pearce, 1994; Scholze, 2004; Hein, 2007; Korff et al., 2007). There is some empirical work proving that engagement with originals leaves a stronger impression compared to photographs or replicas (Frazier et al., 2009; Newman & Bloom, 2012; Newman et al., 2011). And although digital technologies open up new forms and practices of interaction and engagement with art and cultural heritage, to see a famous painting for the first time in your life remains to be a potentially unique experience, a source of inspiration or the birth of a new fascination (Kirchberg & Tröndle, 2012). The intrinsic human desire to experience the original comes along with the high social prestige that is associated with it (Weindl, 2019). Moreover, the value of an original is inseparably associated with the (exhibition) venue as the specific place where the original is preserved and presented. Sometimes, original objects as parts or even places of spiritual practices and rituals are endowed with a religious and social meaning as well as a 'symbolical value' (O'Toole, 1993).
From a researcher's perspective, the original appears as an infinite object of research. New technologies are increasingly providing new opportunities to capture data that was previously impossible to collect. A digital twin only contains the data that is accessible at the time of its digitization. A digital twin, even if it may superficially resemble the original perfectly, is thus always incomplete. If the original is destroyed afterwards, all information that could have been captured later by new technologies is lost. In museums as public institutions, research and preservation of originals can be made transparent and tangible to visitors. Moreover, the heritage site is an open space for research and culture, and the place where fundamental research is done on the provenance of things, which would hardly be possible without the originals. An important topic that is not discussed in detail here, but which should also not be ignored, is the question of the durability of data carriers and the constant advancement of digital formatting.
The social values of the original (and the venue) can be differentiated in four aspects: contact zone, subversion and contra-hegemonial narratives, remembrance, and architecture. According to Clifford (1997), from the museum's democratic task of making cultural heritage publicly accessible follows an important function: to provide a contact zone for the different social groups. Furthermore, the museum is able to challenge and counter prevailing opinions and hegemonial narratives dominating the public discourse through their exhibitions and research on originals (Schilling, 2020). The research on originals also constitutes an important element of remembrance work and identity creation concerning the history of a nation or region. Last but not least, the spatial experience is an important aspect of visiting a heritage site.
Despite all arguments for preserving originals, it is ultimately not possible to preserve every original cultural asset. This leads us to the question which objects we as society consider to be a priority for preservation. As cultural heritage is a public matter and of social importance, this question is definitely a political one and should be discussed as transparently as possible (Leimgruber, 2017).

As described above, heritage institutions have a variety of digital technologies and solutions at their disposal to leverage the full value of cultural assets. But it is necessary to prioritize them due to financial or other restrictions and according to their impact, considering the needs and expectations of their visitors and staff. To identify appropriate products, levels or types of digitalization for the visitor journey, the following section is based on a third preference-based method, namely the conjoint analysis. The aim of our investigation was to examine the method's suitability to identify the crucial factors to enrich the visitor journey, to improve the accessibility of cultural heritage, and to facilitate the knowledge transfer to the visitor.

In times when people expect digital offers in all areas of life, digital technologies can help to keep visitors' interest and to attract new visitors. This assumes that the digital offer is adapted to the needs and wishes of the target audience(s). For a realistic planning of the visitor journey, it is necessary to prioritize not only individual (analogue and digital) components, but also their combination. If one considers the conception of an exhibition as a product to be evaluated by potential visitors, using the conjoint analysis can be a way to investigate the preferences of (potential) visitors. In the business sector, a conjoint analysis is often carried out before introducing new products to the market.

Figure 8: Showcase with the original of the Maya manuscript Codex Dresdensis
© Deutsche Fotothek / Rous, André



3.1 Conjoint analysis design

Like the contingent valuation, the conjoint analysis (CA) belongs to the methods of revealed preference. While the CVM queries the preference for a specific offer (scenario), the CA allows a more differentiated choice to be made between different offers, whereby the importance of individual components can also be recorded. Potential customers are asked to indicate their preferences with regard to various product attributes and their possible levels. This can be done either by assigning a (monetary) value or by ranking the options. Specifically for the heritage sector, components (attributes) can be identified for an exhibition (product) that are conceivable in different variations (levels). It is assumed that the partial benefits of the various attributes add up to the total benefit of the product.

The great advantage of the CA is that potential products with different levels of attributes are directly compared with each other and preferences are queried in a very concrete and realistic way, even for hypothetical or future scenarios. The distortions to be expected due to the hypothetical answers can therefore be assessed as relatively small. However, it should be ensured that the respondents are not presented with too many product variations in order to avoid being overloaded with information and choices.

However, the number of product profiles or concepts required for the statistical evaluation depends on the number of attributes and their levels considered. In the case of two attributes with two levels each, at least four concepts have to be presented to the respondents. In the case of three to four attributes each with two levels, there are already eight concepts that the respondents have to rank. After that, the number of required product variations increases significantly. As such it becomes no longer manageable for the respondents in a written survey, with the risk of yielding unreliable results.

The goal of our 2022 case study was to use the CA approach for more complex products while reducing the number of product variants to a manageable level. The subject was the redesign of the exhibition concept for the Maya Codex exhibited at the Treasury of the Saxon State and University Library Dresden (SLUB). In addition to the on-site survey using the travel cost method (see previous section), the CA design was used in the context of a representative population survey with 1,000 respondents (online) and combined with a regression analysis. First, preferences for six attributes (admission, presentation, information content, exhibition format, offers in the exhibition, offers on the Internet) with three to five levels each were queried. Then three exhibition concepts were to be ranked. For a conjoint analysis, 25 concepts would have been necessary here.

With the help of a multivariate analysis (linear and binary logistic regression), it is nevertheless possible to determine the influence of individual levels of attributes on the formation of preferences with regard to the concepts. The aim is to find out which components of a concept are actually relevant for the respondents in the specific combination. In this way, compensating effects can be taken into account that cause preferences in the selection of the exhibition concept deviating from those that were specified for the individual attribute levels. In combination with t-tests, visitors can be divided into groups based on their preferences and their preference formation can be examined more closely. In the case study, for example, certain components such as information on provenance, a dedicated exhibition space, and additional digital offerings led to a higher admission price being accepted than indicated in the individual query. The evaluation confirmed that the combination of CA design and regression offers a good alternative for achieving good results and identifying relevant influencing factors even with a small number of product variations that is manageable for the respondents.

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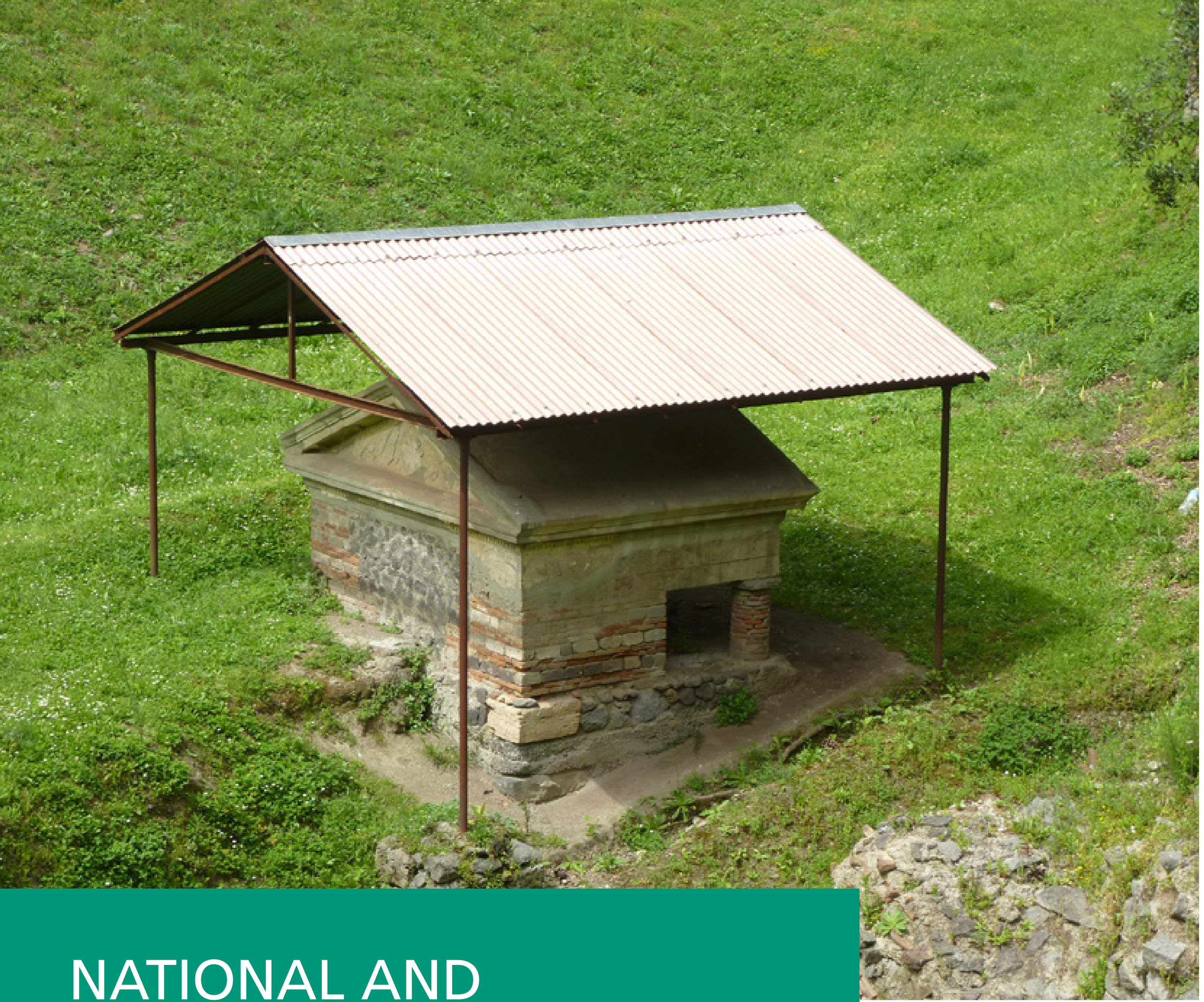

NATIONAL AND INTERNATIONAL ACTIVITIES

The members of the Fraunhofer Research Alliance Cultural Heritage have been very active both at national and international level.

NATIONAL LEVEL

2022 Dataspace Culture – Lighthouse project in the framework of the German National Digital Strategy for the culture and creative industries sector

Fraunhofer FIT (Matthias Jarke and Georgios Toubekis) is co-lead partner together with the National Academy of Science and Engineering responsible for the requirements analysis and technical implementation of the project.
https://digitalstrategie-deutschland.de/leuchtturm-projekte/

2019-2022 Das GRÜNE MUSEUM conference series

Fraunhofer is co-founder of the annual series of the GRÜNES MUSEUM conferences together with Deutsche Kongreß GmbH since its inauguration in 2010. It brings together different sectors from cultural heritage and museums, research and administration and engineering and planning bodies to foster exchange on how to contribute to climate adaptation and sustainability and greening of the cultural heritage sector.
https://www.deutsche-kongress.de/veranstaltung/das-gruene-museum/

»Indoor Air Quality in Museums and Archives« conference series

Fraunhofer WKI (Alexandra Schieweck) is a member of the Scientific Committee.

2021 Woche der Umwelt of DBU (German Environment Foundation)

Symposium on climate adaptation strategies for historic gardens and cultural landscapes
https://www.woche-der-umwelt.de/

2021 Bundesvolontariatstagung (BVT) of DMB (German Museum Association)

Fraunhofer EU Office Brussels (Johanna Leissner), HHI (Paul Chojecki), FEP (Frank-Holm Rögner), IBMT (Peter Weber), IBP (Matthias Winkler und Ralf Kilian), IOSB (Jürgen Moßgraber), and IMW (Uta Pollmer). Two workshops were organized on digitalization and climate change impacts on cultural heritage.
https://www.museumsbund.de/fachgruppen-und-arbeitskreise/arbeitskreis-volontariat/bundesvolontaertagung/

2020 Promoting Europe's Cultural Heritage and Cultural Diversity. Who? How? With Whom?

Presentation of the position paper of ICOMOS Germany at the online symposium in the framework of the EU Council Presidency of the Federal Republic of Germany (Georgios Toubekis, Fraunhofer FIT).
https://www.icomos.de/

Memberships

Forschungsallianz Kulturerbe (FALKE, German Research Alliance Cultural Heritage)

Fraunhofer was co-founder of the alliance in 2006 and coordinates the joint activities of its members: Fraunhofer-Gesellschaft, Leibniz-Gemeinschaft, Stiftung Preussischer Kulturbesitz, Staatliche Kunstsammlungen Dresden, and Sächsische Landesbibliothek – Staats- und Universitätsbibliothek Dresden.
https://forschungsallianz-kulturerbe.de

ICOMOS Deutschland e.V.

Fraunhofer EU Office Brussels (Johanna Leissner) and FIT (Georgios Toubekis) are active members.
https://www.icomos.de/

Deutscher Verband für Kunstgeschichte e.V.

Fraunhofer IPM (Lisa Rentschler) is an active member.
https://kunstgeschichte.org/

Verband der Restauratoren e.V. (VDR)

Fraunhofer IBP (Ralf Kilian, Kristina Holl) and WKI (Alexandra Schieweck) are active members.
https://www.restauratoren.de/

DIN Technical Committee Conservation of Cultural Property
Fraunhofer WKI (Alexandra Schieweck) is an active member.

GAIA-X Hub Germany – Working Group Culture
Fraunhofer FIT (Matthias Jarke and Georgios Toubekis) is founding member.
https://www.acatech.de/projekt/gaia-x-hub-deutschland/

Morgenstadt-Innovationsnetzwerk
Fraunhofer IMW (Urban Kaiser and Uta Pollmer) is a member.
https://morgenstadt.de

Fraunhofer-Netzwerk »Wissenschaft, Kunst und Design«
Fraunhofer IWS (Annekathrin Mäurer), IMW, ISC (Sabrina Rota), and WKI (Alexandra Schieweck) are active members.
https://art-design.fraunhofer.de

GCTP-FACH (German Construction Technology Platform – Focus Area Cultural Heritage)
Fraunhofer UMSICHT (Erich Jelen) and WKI (Alexandra Schieweck) are active members.

NIKE Netzwerk (Network for Interdisciplinary Protection of Cultural property)
Fraunhofer UMSICHT (Erich Jelen) is an active member.
https://netzwerke.bam.de/Netzwerke/Navigation/DE/Netzwerke/NIKE/nike.html

INTERNATIONAL LEVEL

2019-2026 EU Commission Expert Group Cultural Heritage
Johanna Leissner (Fraunhofer EU Office Brussels) was appointed as member in her personal capacity 2019-2022 and her membership was extended recently until 2026.

2022 EIT Knowledge and Innovation Community (KIC) Culture & Creativity
In June 2022, Fraunhofer won the competition of the European Institute of Innovation and Technology (EIT) for the new KIC (Knowledge and Innovation Community) partnership on Culture & Creativity together with 50 consortium partners from 20 European countries. The EIT Culture & Creativity partnership is coordinated by Fraunhofer (Johanna Leissner, Sabrina Rota, Fraunhofer ISC) who serves as lead technology partner including 13 Fraunhofer institutes (IAP, IIS-EZRT, IMW, ISC, ITWM, FIT, FEP, UMSICHT, HHI, IGD, IBP, IZM and Fraunhofer Academy) in supporting the green transformation of Europe's Cultural and Creative Sectors and Industries (CCSI) by connecting creatives, cultural heritage experts and organizations to Europe's largest innovation network. For the 2021 to 2027 funding period, the EIT Culture & Creativity will receive a budget of around €150 million.
https://eit.europa.eu/eit-community/eit-culture-creativity

2022 Climate Conference COP27 in Egypt
Fraunhofer EU Office Brussels (Johanna Leissner) and IAIS (Daniel Luckerath) have been invited to present the topic of cultural heritage in times of climate crisis at the Italian Pavilion.

2022 Conference of the Ministers of Culture of the Euro-Mediterranean
Italy invited for the first time the ministers of culture from all Mediterranean countries to discuss three important topics. One of the three topics was devoted to culture, driver and enabler for sustainable development and the green transition. Johanna Leissner (Fraunhofer EU Office Brussels) was invited to speak about the EU OMC expert group on cultural heritage and climate change.

2021-2022 EU OMC (open Method of Coordination) Expert Group of Member States on Strengthening Cultural Heritage Resilience for Climate Change
Johanna Leissner (Fraunhofer EU Office Brussels) was appointed as German delegate and was elected as chair of the OMC expert group.

2021 Italian Presidency of G20
First time that at G20 the ministers of culture have been meeting. In preparation of the ministerial meeting a preparatory webinar was held on 12 April 2021 on the topic addressing the climate crisis trough culture: preserving heritage and supporting green transition. Fraunhofer (Johanna Leissner) was invited to give a presentation on climate change impacts on cultural heritage.

2020 German Presidency of the Council of the European Union
At the International Conference on Cultural Heritage and Multilateralism in November 2020 during the German EU presidency Johanna Leissner (Fraunhofer EU Office Brussels) was invited to give a presentation about the protection of cultural heritage from climate change – Europe`s important contribution to sustainable development and Green Deal.

Memberships

Climate Heritage Network
Fraunhofer participated at the founding meeting of the Climate Heritage Network in Edinburgh (Scotland) in October 2019 and joined the Network as the first German member.
https://www.climateheritage.org/

XR4Europe
XR4Europe is the united European XR ecosystem and the network of XR professionals and serves as a European Non-for-Profit Organization. Fraunhofer HHI (Oliver Schreer) is member of the Board of Directors.
https://xr4europe.eu

European Heritage Europa Nostra Awards
Fraunhofer EU Office Brussels (Johanna Leissner) is a member of the Awards Jury 2022 and 2023. Fraunhofer FIT (Georgios Toubekis) is member of the jury & selection committee for the category research.
https://www.europeanheritageawards.eu/

International Association for Science and Technology of Building Maintenance and Monuments Preservation (WTA)
The mission of the international association WTA e.V. is the fostering of research and its practical deployment in the disciplines of building and monument preservation. Fraunhofer IBP (Ralf Kilian) is head of the technical commission "Preventive Conservation".
https://www.wta-international.org/en/

International Institute for Conservation of Historic and Artistic Works (IIC)
Fraunhofer WKI (Alexandra Schieweck) is an active member.
https://www.iiconservation.org/

CEN/TC 346 Conservation of Cultural Property
Fraunhofer WKI (Alexandra Schieweck) is an active member.

International Society of Indoor Air Quality and Climate (ISIAQ)
Fraunhofer WKI (Alexandra Schieweck) is an active member.
https://www.isiaq.org/

Smart Heritage Cities Working Group
Fraunhofer IMW (Uta Pollmer) is an active member.
https://www.eurada.org/euradaactivities/working-groups

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