Digital Twins for the conservation of cultural heritage[1]

Damage mapping and building monitoring with highly detailed 3D reconstructions in collaborative virtual reality

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Introduction

New digital technologies promise considerable optimization for continuous and complete condition monitoring, risk assessment, and efficient renovation planning. The costs for a complete photogrammetric building survey with hovering platforms (Unmanned Aerial Systems - UAS) are already lower than the use of conventional scaffolds. The resulting data can be evaluated anywhere and regularly repeating recordings facilitate the observation of changes. However, the full potential of digital technologies for building monitoring remains untapped. Reasons include the remaining human effort for data acquisition and processing, but above all that lack of accessible technologies for the cooperative and location-independent analysis of highly detailed 3D data. DenkmalDigital, a project within the open research and innovation network "Vogtlandpioniere", explored the technical, economical, and social foundations of an end-to-end digital toolchain for damage mapping and condition monitoring of cultural heritage buildings. The result of this toolchain is a detailed representation of cultural heritage buildings that can be experienced and analysed together in social mixed reality, a.k.a. the metaverse. In addition to such digital innovations, the overarching research network Vogtlandpioniere also produces novel technical-material developments.[2]

Approach

The project aimed to 1. establish conceptual and technical foundations of highly accurate and repeatable 3D reconstruction methods, 2. implement the necessary data structures and system architecture for efficient storage, processing, enrichment, and accessibility of the resulting data, and to evaluate the results with functional application demonstrators.

Two very different buildings in the Vogtland region served as example cases. The fortified church of Döblitz was captured entirely in- and outside with certain areas at particularly high resolution. Two complete acquisitions with about one year in between enabled an accurate

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[1] Session "Cultural Heritage and the Metaverse…" – Chair of Lorenzo Ceccon, Italy

[2] The Vogtand counts around 4.700 historically, architecturally, or artistically valuable cultural monuments. Protecting and reuse them offers an exciting research and development framework for technological, economic, and social innovations. At the same time, this topic offers very many approaches of transferability to other regions with cultural heritage facing similar challenges. There is thus a great networking and transfer potential for knowledge, competences, and experience.

documentation of changes. Hummelshain castle was acquired only from the outside and only once at full extent. In both cases, laser scanning and photogrammetric reconstructions were compared for their respective benefits and limitations. Importantly, all data were georeferenced using tachymetry with selected control points in the surrounding area and on the structure. The control points were also measured with a GNSS Receiver to transfer all local 3D data to the higher-level global national coordinate system. This is a fundamental requirement for the spatial registration of data from repeated measurements.

Acquisition Results

The photogrammetric data acquisition of outside structures was realized with unmanned aerial vehicles (UAV) surrounding the buildings semi-automatically while following a predefined flight path. This allowed for save operation with minimal human interference, while capturing the surfaces from very short distances. The flight paths were automatically derived from low-res photogrammetric reconstructions, which were captured from a save distance [Debus & Rodehorst, 2021]. Automating the data acquisition of the interior is more challenging, since indoors GPS-information is not reliable and operating UAVs are typically not allowed.
A ground-based 3D laser scanner was used to generate high-resolution 3D point clouds for comparison to close-range photogrammetry. An obvious drawback the decreasing point density with increasing distance and angle of incidence of the laser beam as well as shadowing by obstacles. UAVs, instead, may reach all areas of the structure and can maintain consistent capturing conditions. A clear benefit is instead, that the acquisition of object geometry can be done without additional illumination. Additionally, laser-scanning data includes a point-related information on the reflectivity of the object surface, which can be used to derive additional hypotheses about properties, such as moisture or roughness. As an exemplary overview of the photogrammetrically generated data volumes and qualities, the results from the first acquisition campaign at the church of Döblitz are listed in the following table (Tab.1):

	# of photos	*Object resolution*	*Mesh size*
Exterior	*2326*	*0.7 mm/px*	*~ 30,000,000 faces*
Interior	*2503*	*<0.2 mm/px*	*~ 20,000,000 faces*
Wall-painting detail	*707*	*<0.1 mm/px*	*~ 5,000,000 faces*
Floor detail	*234*	*<0.2 mm/px*	*~ 1.000.000 faces*

Tab. 1: Photogrammetrically generated data volumen and qualities of the 3D-model “Church of Döblitz”.

Interactive Visualization of Large Geometries

The condition analysis of buildings requires highly detailed surface information. Extensive data must be processed for their interactive visualization, and it is to be expected that the sheer volume of data will continue to grow in the future. The amount of data does not fit into working and graphics memory of common computing devices and even if it would fit, image generation from geometry large data is time-consuming, hence, not interactive. On the other hand, only a small section of the overall data is visible from each perspective on a building and the full level of detail is not always recognizable. Depending on the screen resolution, therefore, only a small section of the available geometry and texture information is actually visible.

Thus, to realize interactive visualization without compromising visual quality, a level-of-detail (LOD) approach was pursued [Kulik et al., 2018]. Figure 1 shows a photo of the interactive visualization of the church of Döblitz on a multi-user 3D projection screen[3] with an illustration of the LOD pyramid to the right. The highest resolution data in the hierarchy is shown at the base of the pyramid. This is where most of the data is needed, so the pyramid is wide here and narrows towards coarser model representations. The grey area illustrates the available data. In the case of the church model, information with a precision of about one millimeter is available for the entire model.

Figure 1: Virtual illumination of a detail scan with submillimeter accuracy ((C) Bauhaus-Universität Weimar)For particularly interesting areas, models were created with sub-millimeter precision. Since this resolution is not available for the entire model, the pyramid is not completely filled in the lower area. For each new perspective on the data, only a small section is needed. This section through the data is illustrated here in a highly simplified way as a red line. [Kulik et al., 2018]

Metadata Management

In addition to the 2D and 3D geometric shapes, further data must be stored and linked. Primarily, this is general information about the object, followed by descriptions of its condition and state, which are to be supported by photos, plans, drawings, room books and findings – a very heterogenous collection of data and information. The preferred approach is to manage and model the heterogeneous data from the context of inspection and monitoring in a meta-model approach [Taraben, 2019]. There, similar to a library entry, only the metadata of the individual files is modeled, so that all the important information about the content, use, and properties of a file can be retrieved independently at any time.

Application Demonstrators

The project focused on analysis tools to compare data from different points in time, on the basics of persistent annotations of damaged areas, as well as on supporting collaboration locally, across locations and with various visualization and interaction setups (Fig. 2+3). Our application demonstrator featured a virtual lens, suitable for the comparison of data from

[3] https://www.digitalprojection.com/emea/dp-projectors/insight-4k-hfr-360/ (2022/07)

different times (Figure 10) as well as false-color visualization of surface structures. Damage mapping can be performed with annotated line drawings on the geometry.

Figure 2: View of the complete model of the fortified church Döblitz with two virtual visitors in front of the entrance ((C) Bauhaus-Universität Weimar)

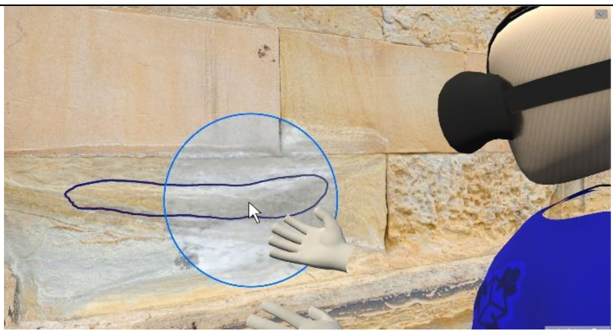

Figure 3: A detail of Hummelshain castle with an overlay of the reflexion coefficients of a registered laser scan in a lens ((C) Bauhaus-Universität Weimar)

Conclusion and Ongoing Work

The proposed digital toolchain demonstrated that different types of structural damages can be clearly identified and mapped if the data recording quality is sufficiently accurate. The interactive comparison of spatially registered 3D reconstructions of different acquisition times, clearly revealed, how much material was lost during that interval at certain surface locations as well as the accumulation of efflorescence over time. It was also observed, that reflectance information from laserscanners may indicate humidity, where it cannot yet be seen in visible light. Considering the economic challenges of maintaining our built cultural heritage, the project demonstrated, that the automatization of detailed photogrammetric data acquisition is practicable at least for exterior structures. This is more difficult to achieve indoors.

The effort and cost for an initial 3D reconstruction may be considered high, but it needs to be stressed here, that a similarly complete analysis on site will not be cheaper, while resulting in less reliable and traceable information. Once a georeferenced 3D model has been created, recurring acquisitions may also be focused on areas with the largest expected changes. The resulting detail reconstruction can be related to the original 3D model, if georeferencing is available or persistent visible features can be matched. It could also be demonstrated that that even extremely high-resolution data can be visualized in real-time using out-of-core data management with level-of-detail rendering technologies.

The fundamental 3D data type used in the project were point clouds, as these allow for appearance-preserving LOD representations [Kulik et al., 2018]. The drawback is a large storage size, which also affects the data exchange among distributed collaborators. The visualization partners therefore implemented an alternative technology that builds on an open-source data-format for level-of-detail triangle meshes and that supports data streaming over any network connection [Ponchio, 2019][4]. The partners are working on the integration with

[4] A simple data-streaming demonstrator can be tested online: https://www.consensive.com/demos/

augmented-reality technologies to support the direct exchange of people on site with visitors of the digital twins in relation to a jointly perceived environment.

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Conflict of Interests Disclosure

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