Article Type: Description (see Introduction for more detail)

Digital Twins for protecting Cultural Heritage against Climate Change

Georgios Mylonas, *Industrial Systems Institute, Athena Research Center, Patras, 26504, Greece*
Athanasios Kalogeras, *Industrial Systems Institute, Athena Research Center, Patras, 26504, Greece*
George Pavlidis, *Institute for Language and Speech Processing, Athena Research Center, Xanthi, 67100, Greece*
Aris Lalos, *Industrial Systems Institute, Athena Research Center, Patras, 26504, Greece*
Ana García López, *Alonso Cano Faculty of Fine Arts, University of Granada, Granada, 18014, Spain*

Abstract—Climate Change has increased both the severity and the frequency of a number of different types of natural hazards. Its impact on Cultural Heritage sites and monuments can be quite significant, thus mandating adequate adaptation and mitigation strategies. Cyber-Physical Systems can help towards this direction by utilizing Cultural Heritage Digital Twins, coupled with AI/ML algorithms facilitating defect/degradation detection and triggering appropriate actions.

Cultural Heritage (CH) is considered as one of the most valuable assets around the world, providing links to our past, contributing to shaping our vision for the future, as well as being a means of promoting our values and way of life. However, CH faces increased risks and uncertainty as regards its protection and maintenance from anthropogenic factors and natural disasters. At the same time, climate change poses additional threats to CH, mandating us to devise innovative and sustainable ways to protect and preserve it. Aside from the dangers related to climate change that threaten CH, a recent report [1] by the International Council on Monuments and Sites (ICOMOS) stressed the role of CH, and the cultural and social values associated with it, in the transition to a more sustainable future and adaptation to climate change, together with the need to accelerate the adoption of mitigation measures and protect it. In recent years, a wave of new technologies has surfaced to help digitize material assets and bridge the real and the digital world, which were adapted and applied also to the field of CH. In this context, [2] surveys the currently used methods in Cultural Heritage digitization with respect to 3D digitization of tangible heritage, which is currently the most common form of such processes.

However, given the growing challenges for CH, new technologies and practices should be applied to improve on the current ones, as well as offer new possibilities on aspects that have not been covered adequately thus far, such as monitoring the structural health of remote monuments, or quantifying the effect of climate change on CH in coastal areas or underwater sites. There is also the potential of AI to revolutionise the ways in which we digitise, monitor and protect CH; AI can be used to assess the state of tangible CH, or simulate the effect of climate change. Sensor-equipped drones can be used to produce 3D representations of monuments and sites at a speed that was unimaginable just a few years ago, while new types of sensors and non-destructive monitoring techniques can offer higher precision and reliability than existing approaches.

DIGITAL TWINS IN CULTURAL HERITAGE

As the next step towards this path, Cultural Heritage Digital Twins (CHDT) have began to surface, incorporating principles from the use of Digital Twins (DT) in other domains, such as smart manufacturing. Regarding the origin of DTs in general, they have progressed from their first use by NASA for simulating space modules in orbit, to holistic representations of more complex processes and systems in recent years. Historically, the “Digital Twin” term was first mentioned

This is the preprint version of an article submitted to IEEE Computer, published with the Digital Object Identifier 10.1109/MC.2023.3290687

in 2003 in the context of product lifecycle management; digital twins quickly expanded to smart manufacturing and Industry 4.0, as well as other domains, like smart cities. In this sense, DTs are ever-evolving, and we are using more flexible ways to define the term.

With respect to CHDTs, there seems to be a lack of a concise definition of what they are and what they are used for. Historically, in the case of built CH (BCH), the CH community has been using the Building Information Modelling (BIM) concept for years, while extending it as the historic building information modelling (HBIM). However, as discussed in detail in [3], although the CH community has started claiming to use DTs, in practice the HBIM approach continues to be the one used.

CHDTs could be seen as an evolution of HBIM, the latter providing the basic digitalization technology, to be combined with simulation capabilities, data fused from IoT deployments, and AI-based predictions, to eventually offer a computational model that "continuously learns from the physical asset and updates itself accordingly" [3]. In other words, a CHDT focuses more on its actual physical counterpart than HBIM, by monitoring and simulating its behavior, integrating real time data, utilizing data analytics and AI for implementing services such as predictive maintenance.

In addition, and with respect to climate change and its effects on CH, here are some aspects that we consider as important elements of future CHDTs:

Climate change & environmental modelling: satellite-based monitoring will be key to assessing CH vulnerability against climate change-related factors; using such data, more reliable models for capturing the long- and short–term effects of climate change, waves and floods on CH sites can be produced.

Structural Health Monitoring: to provide comprehensive structural assessment, developments for global and local damage identification in CH sites should be explored, utilizing tools based on AI/ML, IoT sensors (e.g., accelerometers), photo-acoustic methods and data fusion to continuously monitor CH assets and update their digital counterparts.

Multimodal Degradation Identification: Degradation is a result of conditions that may negatively affect the original structure of CH assets. New tools for automatic degradation detection should be used to facilitate such tasks that traditionally require huge effort and expert knowledge, e.g. by automating the process of monitoring the degradation status of a large-scale CH site.

Spectroscopic Metrology for Chemical analysis of CH artefacts: spectroscopic techniques can facilitate the analysis of complex organic and inorganic materials. In this context, they can help track the status of aspects such as pigments and dyes, providing also valuable input for modern endangered CH assets [**?**].

Citizen science for CH monitoring: ambitious goals or policies cannot rely on technologies alone; citizens and social innovation could be a key factor towards turning political commitment into reality. Citizens and experts can provide input e.g., through smartphones to monitor degradation, or annotate image datasets and train/extend models.

Fig. 1 provides an illustration of an example scenario, where a variety of methods (including satellites, drones, IoT sensors, sensor-equipped buoys and expert/visitor smartphones) are used to produce a digital "living" model of a CH site situated at a coastal area. The digitized site can also include underwater areas, while the modeling of sea waves and currents can be crucial as well. The data collected can be used in local climate and sea wave/currents models to produce macro-models for simulating the effect of climate change at large, while IoT data and 3D models work at a micro scale to continuously feed data to the CHDT and, together with the macro models, produce more accurate predictions or suggestions to the experts.

THE WARMEST SOLUTION

As an example of a solution targeting this area, the WARMEST[1] (loW Altitude Remote sensing for the Monitoring of the state of cultural hEritage Sites: building an inTegrated model for maintenance) EU research project aimed to optimize maintenance in cultural and natural heritage sites through the introduction of novel technologies and tools to collect and analyse data, as well as the creation of a Decision Support System. In this context, WARMEST implemented a *Deep Multimodal Degradation Identification* solution, as a part of the equation. As mentioned above, such a process can be used to automatically detect parts of structures or artefacts in CH sites that have some kind of defect/degradation, thus helping to automate the process of monitoring built CH at scale and accelerate mitigation actions to protect it. For instance, consider a scenario where a drone is used to periodically scan a large CH site that is threatened by climate change, and the data is then fed to a system to pinpoint areas of concern to experts.

In terms of implementation, the system focuses on generating differential 3D saliency maps. At this point it should be mentioned that saliency maps correspond to textures that highlight the regions on which people

[1] WARMEST EU Horizon 2020 project website, https://warmestproject.eu/

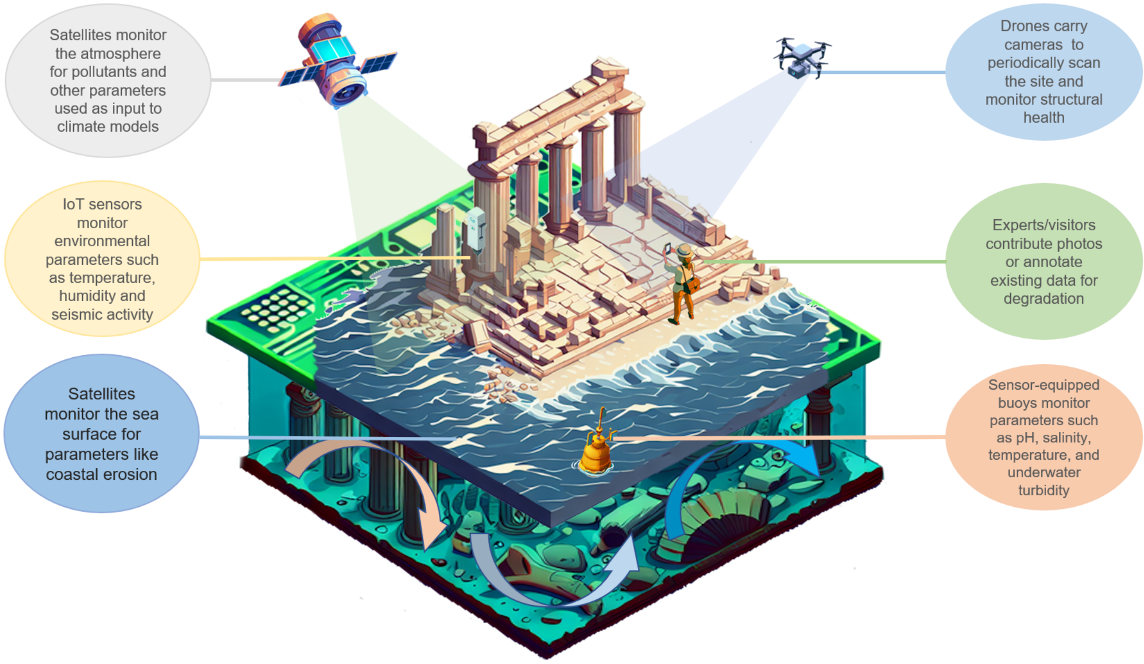

FIGURE 1. A high-level view of the parts currently used to create a Digital Twin for a coastal Cultural Heritage site.

eyes focus first and reflect the degree of importance of 3D areas to the human visual system. The differential saliency maps are calculated over 3D models that have been reconstructed via Structure from Motion techniques [2] (SfM) in two different time instances and capture differences on the saliency features that usually correspond to defects. Those models have been originally deployed for generating 3D saliency maps using baseline traditional methods [4], which are later used for training deep neural networks that will facilitate the saliency extraction problem in a cost-efficient manner. After the completion of the training process, the trained model can be used for the automatic extraction of saliency maps for any other new 3D model. To mitigate the complexity both for data generation and inference purposes, the entire mesh is initially partitioned into a number of overlapping patches of equal size. Subsequently, two distinct steps are used to estimate the spectral and geometrical saliency features [5]. The combination of these two features yields the final saliency values.

Once the saliency mapping is obtained, it can be utilized as input to train/fine-tune novel deep neural networks, which subsequently help to identify regions of interest in the scanned cultural sites/artefacts. To evaluate the implementation of this approach, a series of experiments was conducted using dense SfM 3D models reconstructed from imagery captured inside two important European CH sites: the Patio de Leones of the Alhambra complex in Granada, Spain and the cloister of Santa Croce in Florence, Italy.

Fig. 2 provides an illustration of the process: first, a set of photos of a column inside the Alhambra complex in Granada, Spain, are taken, which are then used to produce an accurate 3D model. This model is then fed to the system, which produces the saliency map and pinpoints areas of interest. A web-based tool is available to manually annotate the models, or edit the system-produced annotations. The same method can be applied to artefacts of different size, e.g., a ceramic pot. Such methods can simplify the process pipeline for CH experts (e.g., archaeologists), as well as be used as input models to other tools, thus completing the CHDT picture.

CONCLUSION

Shielding CH from the effects of natural and anthropogenic hazards should be part of current and future actions. The utilization of Cultural Heritage Digital Twins has enormous potential to transform the sector, facilitating and accelerating processes that were either performed manually, or were based on static models. The need to mitigate the effects of climate change and natural hazards is one of the main drivers towards this path, and we anticipate that solutions like the ones

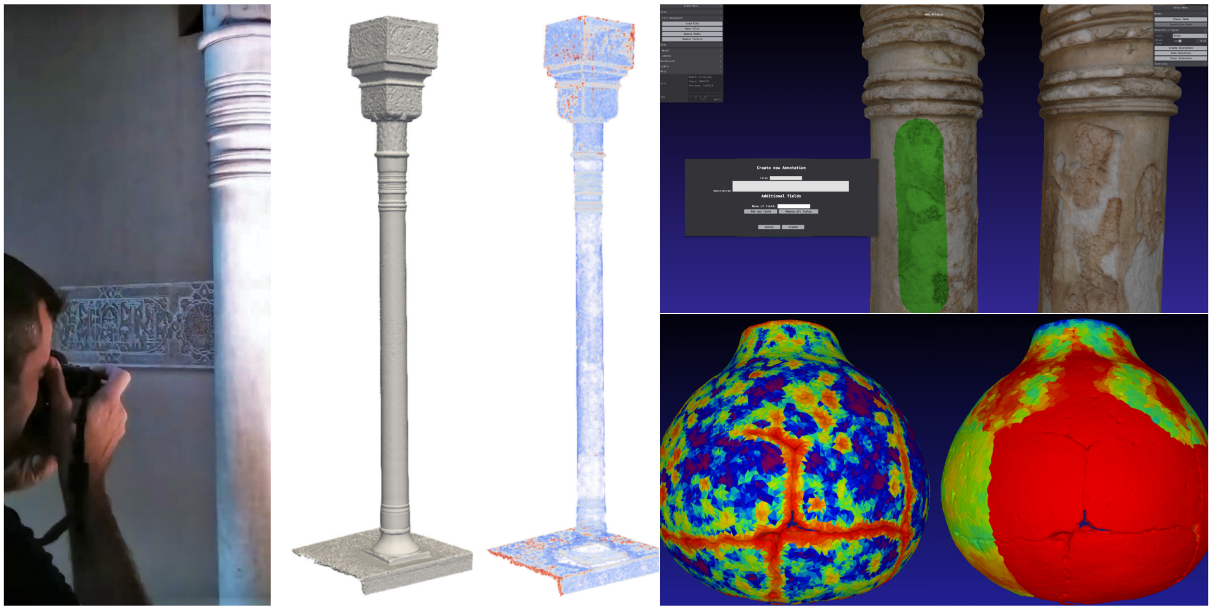

FIGURE 2. Examples showcasing the process pipeline utilized in the WARMEST EU project.

implemented in WARMEST will soon become parts of the toolbox of experts in the area.

ACKNOWLEDGMENTS

This work was partially supported by the European Union Horizon 2020 Research and Innovation Program "WARMEST", through the Marie Skłodowska-Curie Grant Agreement 777981.

REFERENCES

1. Climate Change and Cultural Heritage Working Group International, - (2019) The Future of Our Pasts: Engaging cultural heritage in climate action Outline of Climate Change and Cultural Heritage. Technical Report. International Council on Monuments and Sites - ICOMOS, ICOMOS Paris.
2. Pavlidis, G.; Koutsoudis, A. 3D Digitization of tangible heritage. In Handbook of Cultural Heritage Analysis; Springer: Cham, Switzerland, 2022; pp. 1363–1404.
3. Vuoto, A.; Funari, M.F.; Lourenço, P.B. "On the Use of the Digital Twin Concept for the Structural Integrity Protection of Architectural Heritage". In MDPI Infrastructures 2023, 8, 86. https://doi.org/10.3390/infrastructures8050086.
4. Nousias S, Arvanitis G, Lalos A, Moustakas K. Deep saliency mapping for 3D meshes and applications. ACM Transactions on Multimedia Computing, Communications and Applications. 2023 Feb 6;19(2):1-22.
5. S. Nousias, G. Arvanitis, A. Lalos, G. Pavlidis, C. Koulamas, A. Kalogeras, K. Moustakas, "A Saliency Aware CNN-Based 3D Model Simplification and Compression Framework for Remote Inspection of Heritage Sites", in IEEE Access, vol. 8, pp. 169982-170001, 2020, doi: 10.1109/ACCESS.2020.3023167.

Georgios Mylonas is a principal researcher at the Industrial Systems Institute, Athena Research Center, Greece. His research interests include IoT, pervasive computing, and sustainability-related issues. Georgios received the Ph.D. degree from the University of Patras, Greece. Contact him at mylonasg@athenarc.gr.

Athanasios Kalogeras (SM) is a research director at the Industrial Systems Institute, Athena Research Center, Greece. His research interests include IoT, cyber physical systems, and integration & interoperability. He received the Ph.D. degree from the University of Patras, Greece. Contact him at kalogeras@isi.gr.

George Pavlidis (SM) is a Research Director at the Institute for Language and Speech Processing, Athena Research Center, Greece. His research focuses on digital image and multimedia technologies, content analysis and retrieval, machine learning and artificial intelligence, 3D digitization, and cross-reality applications. Contact him at gpavlid@athenarc.gr.

Aris Lalos (SM) is a research director at the Industrial Systems Institute, Athena Research Center,

Greece. His research interests include AI-enabled Autonomy, Embedded Vision, and Interactive Sensing. He received the Ph.D. degree from the University of Patras, Greece. Contact him at lalos@athenarc.gr.

Ana García López is the Director of the Chair for Innovation in Crafts, Design and Contemporary Art at the University of Granada. Her research interests focus on the relationship between cultural heritage, art and design with the use of technologies, under paradigms of circular economy and sustainability. She received the Ph.D from the University of Granada, Spain. Contact her at agarcial@ugr.es.