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Digital Twin: a new perspective for cultural heritage management and fruition

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ABSTRACT
This paper describes the example of an interesting distance visit approach carried out during the COVID-19 emergency, applied to an underground oil-mill in the town of Gallipoli (Puglia, Italy). The limitations of access for people with disabilities and the complete closure of Italian museums during the emergency have suggested the development of an immersive platform, in the broader perspective of using the output in accordance to digital twin perspectives. Then a tool to support an innovative visit method has been realized: a virtual visit assisted by a real remote guide, hereinafter referred to as "Live-Guided Tour" with e-learning functionality. All this has been made possible starting from a three-dimensional model of an underground oil-mill, from which we extracted the stereoscopic scenes. The stereoscopy is very important for the overall success of the project, because this aspect influences the level of interest, the immersion and the ability to generate emotion and wonder. To the best of Author's knowledge, this is the only system available today for a shared virtual visit for an inaccessible context, which implements many features of a VR visit in a multi-user and multi-platform environment.

Section: RESEARCH PAPER

Keywords: Digital twins; oil-mill; photogrammetry; 3D; virtual visit

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1. THE DIGITAL TWINS, NEXT FUTURE

The term digital twin was originally developed to improve manufacturing and industrial processes [1]. Digital twins were subsequently defined as digital replications of physical entities that enable data to be seamlessly transmitted contents from physical to virtual worlds. Digital twins facilitate the means to monitor, understand and optimize the functions of all physical entities and provide people continuous feedback to improve quality of life and well-being [2].

Digital twin is at the vanguard of the Industry 4.0 revolution enabled through advanced data analytics and the Internet of Things (IoT) connectivity. IoT has increased the volume of many heterogeneous usable data from manufacturing, healthcare and smart city applications [3]. The IoT environment provides an important resource for predictive maintenance and error detection, in particular for the future health of manufacturing processes and smart city developments, while also aiding in fault detection and traffic management in a next smart city. Since a perfect integration between IoT and data analysis will be necessary in the near future, this important need will be possible thanks to the creation of a connection between physical and virtual twins. A digital twin environment allows smart cities for quick analysis and, using 5G network, real-time decisions can be made through an accurate analysis.

The first terminology was given by Michael Grieves, Research Professor (Florida Institute of Technology) in a 2003 presentation, and later documented in a white paper where the future developments of digital twins are traced. The first articles make a definition of "digital model". These are described as a digital version of a pre-existing or planned physical object. An important distinguishing feature, with the old definition of "digital model", is that there is no form of automatic data exchange between the physical system and the digital model. This means that a change made to the physical object has no impact on the digital model, and vice versa.

When data run between an existing physical object and a digital object, and they are fully integrated in both directions, this establishes a "digital twin" reference. A change made to the physical object automatically leads to a change to the digital object and vice versa. A digital twin consequently provides an intimate connection with his real counterpart, and in some way determines an influence on it. An environmental monitoring system on the real object will be evaluated on the digital twin and, consequently, interventions on the internal microclimate, for example, will be managed remotely with effects on other environmental parameters. If a digital twin is connected with IoT systems or sensors, it allows a remote intervention that by the digital object affects the real object. In the near future, the use of digital twins will potentially be very common, they will grow in step with the rapid developments in connectivity via IoT within a smart city. As the number of smart cities grows, so will the use of digital twins. Moreover, the more data we collect from the IoT sensors embedded in our main services within a city, the greater the opportunities for economic growth and development of new innovative start-up able to provide those services will be. Digital twins can be used to aid in the planning and development of current smart cities and to help with the ongoing development of new ones in the world of energy saving. This data can facilitate growth by being able to create a living test bed within a virtual twin that can achieve two goals: first, to test the scenarios, and second, to allow digital twins to learn from the environment by analysing changes in the collected data. [4]

Therefore, digital twin can evolve to become a true digital replica of potential or actual physical resources (physical twin), processes, people, places, infrastructures, systems and devices that can be used for various purposes. We can compare digital twin to other mirror model concept, which aims to model part of the physical world with its cyber representation [5].

2. DIGITAL TWINS FOR CULTURAL HERITAGE ENJOYMENT: A FUTURE PERSPECTIVE?

From this analysis, however, a criticality emerges. There is still a real difficulty in fully assuming a cultural heritage as digital twin, because as Grieves himself pointed out, a Mirrored Spaces Model always refers to an extremely dynamic representation [6]. The real dimension and the virtual dimension, in the primitive definition, remained connected during the entire life cycle of the system, going through all the phases of creation, production and operation. The definition of digital twin is still closely related to industrial production and its processes [7]. A necessary condition for the realization of a digital twin is the existence of physical products in real space, of virtual products in virtual space, and systems for connecting the flow of data that unite physical and virtual space.

Over the past 30 years, product and process engineering teams have used 3D rendering and process simulation to validate the feasibility of an asset within a production process. A 3D model allows the entire system to be merged into a virtual space, so that conflicts and critical issues are discovered more economically and quickly. With these premises, a product is only released when all the problems have been solved. Thanks to digital twin it is possible to test and understand how systems and products will behave in a wide variety of environments, using virtual space and simulation as a predictive moment. All this is possible by combining different technologies related to a single database that will contain all plant or product design data, simulation software, real-time data from the production environment and much more. The advantages are many, starting from the possibility of easily accessing data from many different sources, aggregating and visualizing them through a single synchronized and shared portal, and being able to add contextual information.

Many of the requirements among those listed will certainly not be met, due to the very nature of cultural heritage, which is not linked to the production industry. However, we can certainly imagine a future populated by digital twins of cultural heritage that systematically respond to a series of needs, ranging from conservation to knowledge of places, to enjoinment and enhancement.

In a new perspective of growth and use of the IoT, digital twins can become real “models of knowledge”, integrated into a wider domain of elements. We can create a cyberspace with digital models that can allow facilities in a city with obstacles and limitations of use. Indeed, with other assumptions, this path has been opened for many years. In fact, the term digital heritage refers to the cultural heritage, which exists in relation to a digital model, a copy or replica of the physical (real) model, but often it is intended as “digital media in the service of preserving cultural or natural heritage”. Therefore, if the digital heritage is within a broader system (for example of a smart city), where each digital resource communicates or it is connected in different ways to the others, then this could mean an evolution of the digital heritage in the direction of digital twins [8].

Next to an environment monitored by sensors and intelligent systems, it is possible to achieve an effective way of using digital models to ensure an ideal interaction with real spaces. This has always been done in the past: virtual archaeology pursues precisely these objectives, but if these models are connected to each other in a smart city, then they will also be part of an ecosystem. Considering that, it is possible to convert old digital scenarios with smart visits of cultural heritage in immersive and participatory virtual environments, within enabling platforms. The starting point is to make the virtual visit more collective, more interactive and more participative, with the possibility of

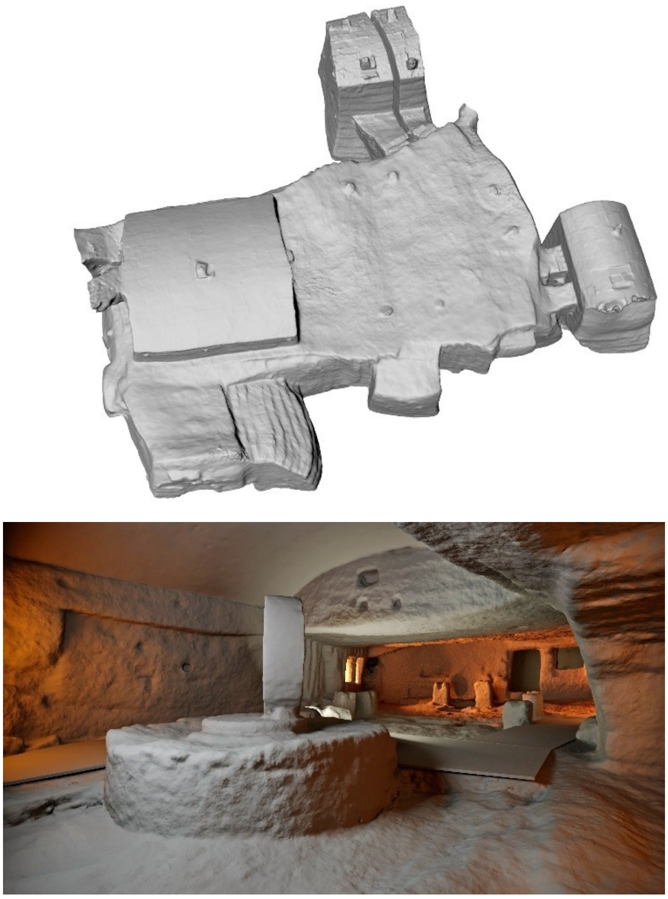

Figure 1. The complete 3D model of the oil mill and the first light simulation without textures.

receiving a valuation of the understanding level of the communicated contents. The ultimate goal is to integrate these virtual scenarios into an IoT system, where each of them can be connected with others 3D models which can be used in a digital twins perspective. These 3D scenarios can give information on their physical counterpart, information relating to environmental monitoring, energy consumption, state of conservation. At the same time we can use these models to cross the gap related to visitors with disabilities, or use them effectively as a distant visit tool. The important condition to make the digital twin effective with regard to communicative issues, is to obtain an ultra-realistic virtual restitution, in order to be able to offer emotion to the visitor, an emotion similar to the one achieved during a real visit [7]. The second condition is to have an accurate 3D model (Figure 1). Physical measurements can be effective, obviously, only in a reliable 3D space. When these two requirements are both satisfied, it is possible to deal with all the developments according to the world of digital twins.

3. LIVE-GUIDED TOUR

An example of this approach has been carried out during the COVID-19 lockdown, applied to an underground oil-mill in the town of Gallipoli (Puglia, Italy) [9]. The main and most profitable activity, which has ruled the fortune of Terra d'Otranto for many centuries, has been the oil industry, carried out in over 2500 hypogeous and semi-hypogeous *trappeti* (oil mill). In these sites only *lampante* oil (oil for lamps) was produced, i.e., for industrial use, exported mainly to France and England, where it was used as a lubricant in wool industries and soap factories [10]. The oil mill described here is entirely dug out of the rock and is actually preserved in its original form, with a very "organic" appearance, without regular or squared surfaces. The three-dimensional survey must be carried out taking care to faithfully reconstruct its natural morphology, but above all the colour of the walls and the interior dark aspect. The limitations of access for people with disabilities and the complete closure of Italian museums during the COVID-19 emergency have suggested the development of an immersive platform, in the broader perspective of a use of output as digital twin. Then a tool to support an innovative visit method has been carried out: a virtual visit assisted by a real remote guide, below referred to as “live-guided tour” with e-learning functionality. This tour mode allows to organize virtual tours for groups of visitors who can simultaneously connect to the web and participate in a tour in which a real guide, which is also connected remotely, organizes and sets the visit, providing information to visitors. A webApp allows to accompany customers, students or colleagues in a shared virtual walk [11]. The virtual tour is similar to a video conference in which the interactive content viewed on PC or portable device can be controlled by any participant. The guests of the tour may be accompanied by a real guide in a trip where the guide (the host) has the ability to control the scene displayed by visitors, or to let them freely choose where to turn its gaze. Guests can then break away at any time by driving control and freely explore every scene, without losing the interactivity that characterizes the virtual tour. With a mouse click they can relate to the host location; in the same way, the host can force any visitor to reconnect to his point of view. Since the tour mode is slightly comparable to a video conference, during the visit each participant can take part in the discussion. The host (whether he is an agent, a teacher, a colleague, a tour guide) can call attention to areas of interest in real-time and discuss what is seen at 360° by all. The guest (customer, student, visitor to a museum, etc.) can follow the guide trip or ask permission to check out the tour for everybody. In this case he himself leads the tour: an ideal solution for asking questions about elements and details scene displayed. This type of visit is a significant improvement compared to video conferences with split screen: in this case we have a built-in communication tool in a virtual tour. Each participant will have a name and a small screen that identifies all.

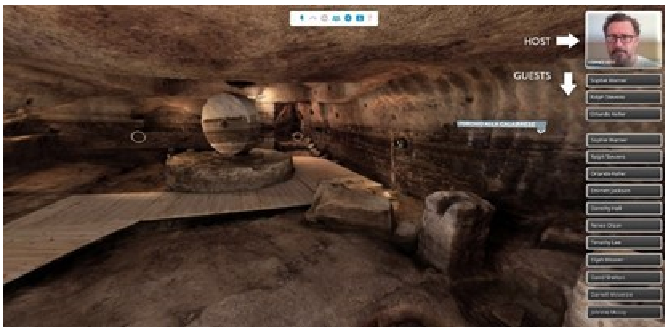

Figure 2. The user experience of live-guided tour.

For the realization of the webApp stereoscopic panoramas have been extracted from the 3D models [12]. The navigation is not conceived as a real time 3D model, but is based on pre-calculated panoramas, which therefore allow the same stereoscopic view of a 3D model, but with a request for extremely low hardware performances. The webApp is available on any device, whether desktop or mobile, so every visitor can also connect their mobile phone. The information elements are available in different types: text, audio, images, virtual reconstructions and videos, all specifically developed to enable you to get the best knowledge of the places. The application has been developed with the features of a webApp, which allows greater flexibility and compatibility with most media and operating systems.

In addition to these features, the webApp, based on 3D Vista software (https://www.3dvista.com/en/), integrates a learning management system (LMS). This application platform allows the development of courses in e-learning mode in order to contribute to the realization of an educational or didactic project, but also to obtain objective results in terms of "evaluation of the communicative effectiveness" within a lesson in a virtual tour. In other words, an LMS platform determines a score that gives the user a level of competence or knowledge. We can consider what benefits this approach can lead to, for example, on construction sites, or in manufacturing environments, to determine the level of competency of employees. Or what benefits it can bring to safety oversight in the workplace (Figure 2).

The use of these VR-based tools has shown greater effectiveness in learning than traditional teaching methods [13]. The solution permits to ask questions to visitors at any time of the tour. They can be conditioned by a previous action, such as the discovery of a hidden element in the scene, after which a question that asks the user about it will subsequently appear. In addition to the questions and answers (simple or multiple-choice questions), queries can contain all kinds of media, including photos, videos, 360º views or 3D models (Figure 3). At the end of a visit session, users will be able to see a score screen that depends on the settings chosen by the author of the tour. The user can download their performance sheet as file.cvs or send it immediately to the LMS. This feature allows the organizers of the visit to collect analytical data of the tour and verify the level of satisfaction reached by the participants.

Figure 3. Final 3D model after bake texturing process. The starting point of digital twin.

4. THE 3D SURVEY

All this is made possible starting from a three-dimensional model of the underground oil mill, from which the stereoscopic panoramas have been extracted. Stereoscopy is very important for the full success of the project. In effect tis his is the aspect on which the level of interest induced in the visitor depends the most [14]. The immersiveness induced by stereoscopic vision is part of an empathic mechanism that can be expressed in the ability to emotionally involve the viewer with a message in which he is led to identify with. As a result, the user will tend to consider the two distinct objects, the digital twin and the real context, as if they were one and the same thing. He may then accept that, during the virtual experience, many of the aspects perceptible only during a real visit can be understood. The immersiveness, if is accompanied by the realism of the restitution, is therefore decisive in considering that the vision obtained with simple 360º panoramas is comparable to that obtainable with a 3D model explorable in real time with hi-end viewers. We can say that the ability to generate emotion and amazement, combined with the sense of presence, is an important element in generating interest and attention during the visit. As a result, greater interest and attention will lead to greater understanding of the communicated message. This explains some of the effort put into generating a 3D model from which stereoscopic panoramas can be derived (Figure 3). Of course, the current technological landscape offers several solutions to obtain stereoscopic panoramas, in most cases obtainable with simple photos [15]. Some manufacturers offer dedicated hardware with up to 12K resolution. The differences between image-based solution and full 3D method are substantial and obvious, but it is worth mentioning here some of the main differences and criticalities inherent in the two methods.

First of all, the pano 360° obtained from photos do not allow to determine the surface morphology of the object, consequently they do not yield metric information in XYZ space. This is a crucial aspect in the use of digital twins since they are characterized by the intimate connection between 3D topology and real space [16]. In the absence of a 3D morphology, it will not be possible to link information derived from sensors and archaeometric, structural and microclimatic analyses relating to specific parts of the asset in study. Just think of the georeferenced superimposition of information and its reading according to layers organized by categories, which is impossible to properly achieve on photographic pano. In the case study presented here, the stereoscopic panos is therefore only one of many media that can be obtained from the 3D model [17]. This is not a starting point but a reading output of the information produced, subsequently organized according to the paradigms of a VR visit. It seems therefore undoubted that the effort to be achieved is to obtain an accurate three-dimensional model, on which all the data relative to the management of the real space connected to its analogous 3D topological space can be hooked. This can be conceived as a geometric space of polygons and as a body of information correlated to the surface colour (Figure 4).

For the virtual use of the collected digital resources, it is crucial to have an extremely realistic three-dimensional model. Realism in this case is not aimed at a cinematic level of representation, but at the best correspondence with the actual state [18]. To this end, a complete three-dimensional model was created using digital photogrammetry techniques, which are now widely used and known to all. The three-dimensional restitution posed many problems of coverage in the hidden areas and of management of photo shooting due to the poor interior lighting, but also to the precise need to obtain a digital twin that restores the same "genius loci" as the real space. In fact, we have deliberately kept the atmosphere of the real space, without making it too artificial or illuminated in a different way than the real space. Approximately 3000 high-resolution photos (21 Mpixel) were then generated, resulting in a mesh resolution of approximately 0.4 mm, which is more than acceptable for the

Figure 4. 3D model of the Calabrian-style press integrated in the VR visit.

purposes of the project and the size of the mill (approximately 250 sqm). The measurements were georeferenced with coded targets, whose coordinates were recorded with a total station.

This has made it possible to keep high the accuracy of the measurements, while keeping fixed the constraints [19]. Due to the computational complexity of the photogrammetric model, the calculation was divided by zones with overlapping of about 10 cm. The main orientation (sparse cloud) was generated for the entire set of photographs, while the dense clouds were calculated in several patches [20]. This solution solves many memory and computation problems, which often prevent the completion of digital photogrammetry projects characterized by a large number of photos [21]. The orientation of the sparse cloud is actually not a very hard problem in terms of calculation, even with huge sets of photos, it is therefore possible to calculate individual chunks while maintaining the correct referencing. The spatial position of the different chunks will be respected even in case of an export to modelling software or BIM [22], [23].

Regarding the texturing process, a texture with a resolution of 15000 pixels x 15000 pixels was calculated for each of the several portions of the model. This process, as expected, causing several problems due to the poor lighting of the interior and the need to shoot the photos with the camera gripped. Therefore, a new set of images was created to solve blurring anomalies induced by depth of field and relatively long shutter speeds (often 1/60 sec). From an operational point of view, the sparse cloud was then calculated with the entire set of photos. In the last phase dedicated to the texturing only the photos taken ad hoc for this

Figure 5. Real photo of the interiors. On the left the original image, on the right the colours have been corrected using the Kodak Color Separation Guide.

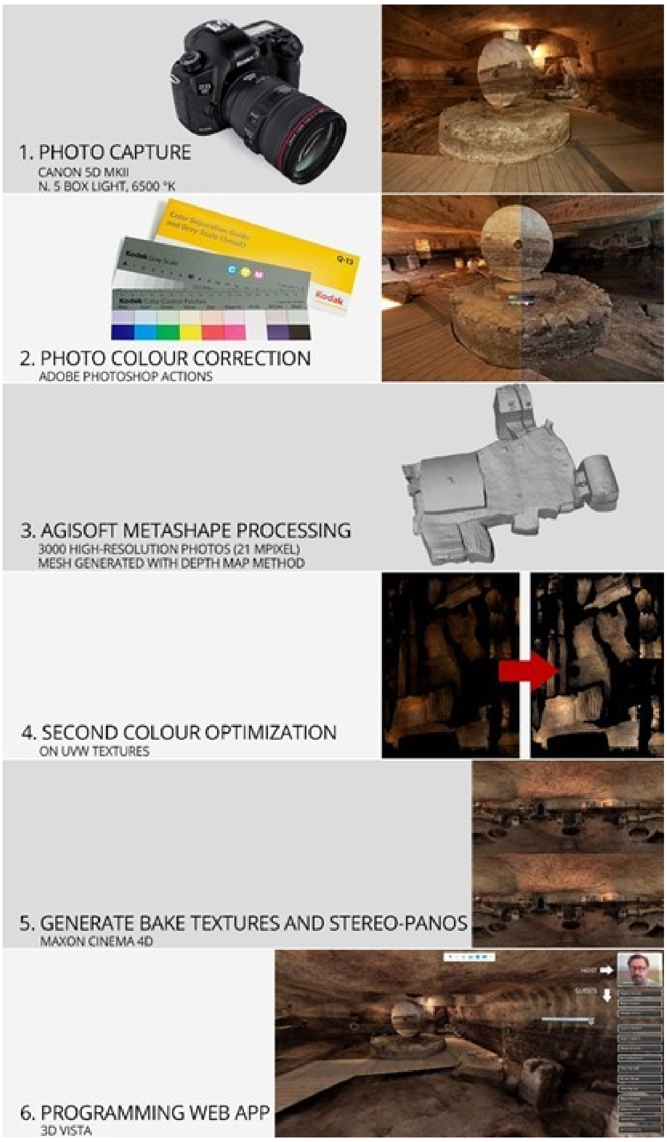

Figure 6. Synthesis of methodological workflow.

purpose were enabled. Basically, we built a very large set of photos needed to get good geometric detail and a set of about 400 photos dedicated to the texturing.

The correct correspondence and reproduction of real colours was ensured by the use of a Kodak Color Separation Guide (Figure 5). The inclusion of the colour scale in the real environment simplifies the correction of the white point of the image, allowing the removal of cast colours [24]. In our case study the dominant colours (cast colours) are not very evident due to the use of controlled lights with 6500 °K temperature [25]. It is not necessary to affix the colour scale on all photos. If these are acquired in the same way and with the same lamps, the correction can be recorded as an action in Photoshop and applied to the whole set of photos [24]. The use of the Agisoft Metashape software has allowed an optimal management of all phases of the survey (Figure 6). In particular, the new mesh creation function was used starting from the depth map instead of the more used dense cloud. This new feature is much more versatile and precise, especially in the presence of dense clouds with a large number of points.

The use of depth maps helps to reduce noise on the final surface while preserving thin structures within the scene. New depth map-based method allows to reconstruct exceptionally

Figure 7. The 3D model with the settling wells in the foreground.

detailed geometry. GPU acceleration allows you to significantly speed up processing with reduced memory consumption compared to previous versions of the software. The final result is shown in the figures on these pages (Figure 3 – Figure 7).

5. CONCLUSIONS

From a morphological point of view, the digital model of the oil mill is therefore a reliable replica of its physical reference. In the case of extraction machines that are no longer conserved, one- and two-screw presses have been included in the virtual tour, taken with the same 3D techniques from other similar contexts. Since photogrammetry ensures excellent accuracy even of the colour data, the 3D model is ready for all subsequent implementations concerning the state of conservation, measurement of volumes, static verification in relation to loads and road surfaces, calculation of energy requirements, etc. At the moment the digital twin allows groups of users to visit remotely this context, in immersive way, with the possibility of extending the visit to other contexts that can follow this management philosophy.

This aspect related to the visualization and use of data belongs to one of the purposes of using these digital resources. The main difference to a classic 3D navigable scenario or a classic virtual tour is a new perspective on the use of these models. They are no longer created with the exclusive objective of obtaining a survey of the actual state, but respond to a new management requirement, which takes into account the potential of 5G, the greater computational capacity of portable devices and IoT (Internet of Things). The 3D object in this case is a 'thing' that has its own consistency, certainly digital and immaterial, but tangible and useful for the management of the physical asset.

Regarding innovativeness in visiting, the live-guided tours are probably the only system available today for a shared virtual tour. But what are the other elements of interest in this project? Firstly the benefits offered by the distant visit modality, in the context of the current pandemic emergency. Not less important the possibility of virtual access for the disabled, in a multi-user and multi-platform environment. Finally, the technological appeal given by the immersive vision and the potentialities related to the digital twin philosophy, still not fully explored in the Cultural Heritage sector.

The long-term goal for us is the creation of an advanced management model. The association between physical object and virtual reality makes it possible to activate a data analysis and monitoring of the systems in such a way that it is possible to operate in predictive mode, identifying problems even before they occur. In addition to preventing anomalies, downtime and inefficiencies, it is possible to develop new opportunities using appropriate simulations and planning future business. By creating a digital twin, it is possible to better understand how to optimize operations, increase efficiency or discover a problem before it happens. The creation of digital twins related to cultural heritage allows the making of models representative of reality, to be used for conservation purposes, for knowledge and for overcoming physical and cognitive barriers.

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