

# HIGH RESOLUTION 3D MODELLING OF CULTURAL HERITAGE

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**Abstract.** The article presents an ongoing work performed in the research project SCAN4RECO concerning multimodal and multispectral scanning of Cultural Heritage (CH) assets for their digitization and conservation via spatiotemporal reconstruction and 3D printing, funded by the European Commission under Horizon 2020 program. We present here the project, as well as research and development research results achieved to date. A combination of visual and penetrating scanning technologies, including infrared, Raman and X-rays produce layered 3D models of an object, allowing for detection and quantification of e.g. underlying layers/images. Subsequent 3D post processing focuses on simulating expected degradation over time under known environmental conditions. However, in this article we focus on the modelling of object geometry using primarily photogrammetric methods to achieve very high object resolution using consumer types of devices, thus making such an approach attractive to professions and hobbyists alike.

## 1 Introduction

The cultural heritage and the way we preserve and valorize it is a major factor in defining Europe's place in the world and its attractiveness as a place to live, work, and visit; a powerful instrument that provides a sense of belonging amongst and between European citizens. The need to preserve, provide advanced access to and understanding of cultural heritage is clearly of utmost importance, especially when considering its wealth throughout Europe. The European cultural heritage is enormous, with a vast and rich variety of cultural items, ranging from buildings to museum artefacts. These items consist of materials of diverse types, the condition of which deteriorates with time, mainly due to environmental conditions and human actions. The effective documentation of the cultural items, so that information about them is easily accessible to researchers and the public. The preservation of objects against the effects of time to be passed unaltered to next generations, are also matters of uttermost importance and have attracted significant focus.

The documentation of a collection of cultural items involves the integration of information concerning various aspects of an object, such as its shape, its appearance, the materials that it consists of, etc., in a unified entity, which can be easily archived and be accessible to researchers, or to the public. Such information is useful to history and archaeology scholars, as well as to people involved in the preservation of cultural objects. By allowing public access to this information, the cultural heritage becomes more attractive to the public. The purpose of documentation is to create a complete digitized representation of a cultural object, which can be stored indefinitely and be accessible to everyone. However, the proper and complete documentation of the large numbers of cultural objects poses several difficulties. The collection of sufficient information and photographic material from each individual object is a time-consuming process. Currently there is a lack of a unified format for the storage of the collected information, one that makes it easy for individuals of different professions and expertise to have an overview of an item and gather the information they need. Apart from documentation, the theory of preservation deals with minimizing the deterioration and loss of items of cultural heritage. Preventive conservation is especially of interest, since it allows the preservation of the state of an object, without affecting its appearance.

Factors responsible for the deterioration of the state of cultural items, in case of indoor environments, include but are not limited to, humidity, temperature, exposure to light, as well as the effects of human activities, such as the transportation of the items. These factors are eliminated by keeping the cultural items in specifically designed facilities, such as museums and galleries, where environmental conditions are controlled by following specifications established after extensive research. However, there is a lack of research concerning the effect of the environment and the means to eliminate it, in cases of uncontrolled indoor environments. Such cases include objects and artworks hosted in historical buildings and monuments of

public access, where people activities are not restricted, as in museums. The increased human activity, in combination with the uncontrolled environmental conditions of such facilities affects the objects of interest in a significantly higher degree, than the controlled environment of a museum.

In this respect, several monitoring and simulation technologies can be effectively used in order to assist in the documentation of cultural objects, as well as the evaluation of the effects of the environment on them and the development of procedures to handle those effects, in order to achieve preventive conservation. Optical, infrared, ultrasounds, x-ray and other elaborate sensors can be used to scan an object and create a rich 3D representation of it. The 3D representation is the most complete way to represent the whole structure of an object. Apart from the shape and appearance of the object, other information, resulting from various sensors, can be integrated in the 3D model, such as the materials of the object and stratigraphy information. Automatic missing part reconstruction techniques can also be adopted, to fill missing parts of the object and make the whole shape of the object available. Such rich representation, containing multimodal information, can be used by historians to have an enhanced overview of an object and to study its structure and properties. Moreover, by providing public access to this information, non-experts can virtually examine a work of art, without having to visit a museum and in ways that a visit to the museum would not allow.

The rich 3D representation of a cultural object is also valuable for conservators. The 3D model constitutes an accurate virtual representation of the object and contains information about its materials and its internal condition. It thus allows the conservators to view areas of the object, which are susceptible to damage from external factors, without needing a direct access to the physical item, reducing thus, the amount of intrusion. In addition to the information of the 3D models of the objects in a facility, temperature, light and humidity sensors can constantly monitor the environmental conditions around a cultural item, for the conservation personnel to be aware of fluctuations of these conditions, which may result in the deterioration of the object. By combining environmental monitoring with continuous observation of state of an object, by updating its 3D representation, the conservator can gain an overview of how the state of the item is affected by environmental conditions over time. Such measurements can assist in preventing damage to the items and in designing strategies for better preservation.

To answer the needs of the users and the market, the Scan4Reco project aims to develop a novel, portable, integrated and modular solution for customized and thus cost-effective, automatic digitization and analysis of cultural heritage objects (CHOs). One of the main goals of the project is to create highly accurate digital surrogates of CHOs, providing also detailed insight over their surface and the volumetric structure, material composition and structure of underlying materials, enabling rendering either via visualization techniques or via multi-material 3D printing.

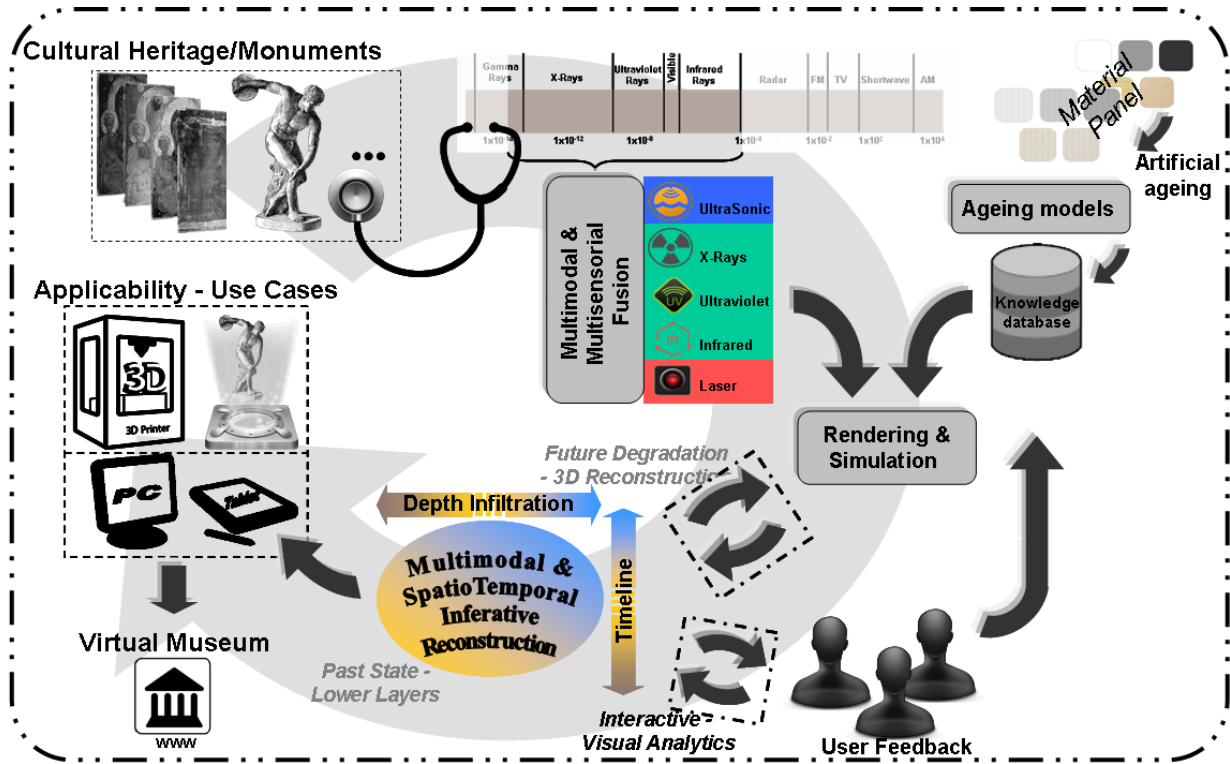
The project aims to analyze object with various scanning technologies with aim to understand the heterogeneous nature and complex structures of material used, to identify the broad and varied classes of materials and to understand their degradation mechanisms over time, deriving context-dependent ageing models per material. Single material models are going to be spatiotemporally simulated, based on environmental phenomena modeling, so as to collectively render imminent degradation effects on the multi-material objects, enabling prediction and recreation of their future appearance, as well as automatic restoration, reaching even back to their original shape. Scan4Reco will further facilitate conservation, by indicating spots/segments of cultural objects that are in eminent conservation need and require special attention, while suggestions will be provided by a dedicated Decision Support System (DSS), over conservation methods that should be followed.

Research results will be validated on real case scenarios involving heterogeneous objects of diverse sizes and materials, in two real-world pilot use cases. To enhance the accessibility of the digitized cultural objects to the scientific community, field experts and the public, a virtual model of a museum will be launched. The impact of Scan4Reco is expected to set the basis for the widespread adoption of sensor-based systems across the spectrum of cultural heritage objects and their conservation.

## **2. Architecture of the SCAN4RECO System**

To address the observations above, the Scan4Reco project aims at delivering a cost-efficient, portable, integrated system, based on multi-modal and multi-discipline, modular, scalable and open-architecture

(presented in Fig. 1) extendable platform that will be able to provide multispectral scanning of a variety of cultural asset (e.g. wall-paintings, painting, metallic objects of various sized, carved marble, statues, etc.) non-destructively. It will efficiently process the multi-sensorial input in such a hierarchical way, to produce VR models of improved quality and information according to the demands of the end-user or the use-case/application itself, utilizing each time a diverse set of sensors. This way the complexity and the quality of the multi-layered and multi-dimensional VR model of the cultural object of interest will vary per demand.



**Fig. 1.** Conceptual architecture of the Scan4Reco system

An important part of the project focuses on the study and modeling of materials commonly found in a variety of common cultural objects. This way, inter-disciplinary knowledge (e.g. physics, chemistry, history, etc.) is combined with computer science (e.g. spatiotemporal simulation, 3D rendering, DSS suggestions, visualization, etc.). The ultimate goal will be not only the material identification, stratigraphy revealing and automatic, accurate digital 3D representation and reconstruction of the object in its original state, but also the automatic inference of both previous states (i.e. restoration) and forthcoming state/shape of the object in certain times in the future, leading thus, to a 4D representation in Virtual Reality (VR) where three dimensions represent spatial information (including depth information of possible stratigraphy under the visible surface) and an extra dimension corresponds to temporal changes through simulation.

### 3. Photogrammetric 3D modelling of cultural objects

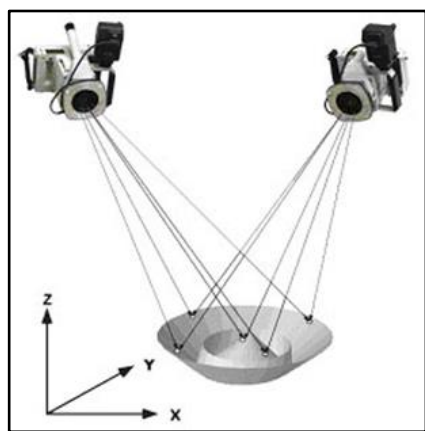
One of the main components of the Scan4Reco system is the 3D scanning of the object geometry. It serves as a pre-requisite for being able to visualize together multiple results from a variety of surface and penetrating scanning of small parts of the object. Those include e.g. multispectral visualization from infrared to ultraviolet, depth scanning like X-ray or Raman, to micro surface variations (roughness) using microprofilometry. Furthermore, object geometry serves also as a reference for simulated prediction of future degradations of the object over prolonged periods of time. Such changes involve both physical erosion of the surface as well as chemical changes that affect the steadiness of the object surface and give raise to speeding up of the object deterioration. Since such changes occur very slowly, having a very accurate and high-resolution 3D object representation is even more important.

Over recent years, 3D scanning has become part of a coherent and non-contact approach to the documentation of cultural heritage and its long-term preservation. High-resolution 3D recordings of sites,

monuments and artefacts allow us to monitor, study, disseminate and understand our shared cultural history – it is essential that the vast archives of 3D and color data are securely archived. An integral component of this work is to record surfaces and forms at the highest possible resolutions and archive them in raw formats, so the data can continue to be re-processed as technology advances. In some cases, the data will need to be re-materialized as a physical object - and this is where a great deal of misunderstanding exists.

Digital models are used to be associated with virtual environments, but now the ability to rematerialize data as physical 3D objects is demanding new explorations into the types of information the data contains. The levels of damage and destruction of heritage sites caused by mass tourism, wars, iconoclastic acts, the ravages of time, commercial imperatives, imperfect restoration and natural disasters has led to a re-evaluation of the importance of high resolution facsimiles. Exact representations are being made possible through advances in 3D recording, composite photography, an assortment of multi-spectral imaging techniques, image processing and output technologies.

Many different 3D scanning methods exist, each with their own advantages and limitations. The challenge is to identify the right system for the right application. No one system can do every-thing. The diverse methods of capturing 3D data evidences this. Time of flight, triangulation, photogrammetry and a host of different approaches are redefining the relationship between image and form. The 3D data can be on a vast scale, recording the topography of a landscape from great distances or it can be close range and accurate enough to document the surface of a carving; marks that are not easily visible to the human eye can be visualized for reconstruction study or condition monitoring. While some systems can obtain color data as well as 3D information, currently no 3D scanner is able to record color to the standard required to produce an exact replica. All 3D recording is based on metrology; the science of making measurements. Outlined below are the main techniques and scanners that are commonly used and the reasons they are used in the way they are. The project needs are twofold, from one side a correct representation of object shape (geometry), from the other one dealing correctly with difficult materials to capture their correct color and appearance. The focus of this chapter is capturing the global shape, whereby some of the presented commercial technologies show potential for correct representation of object appearance as well.



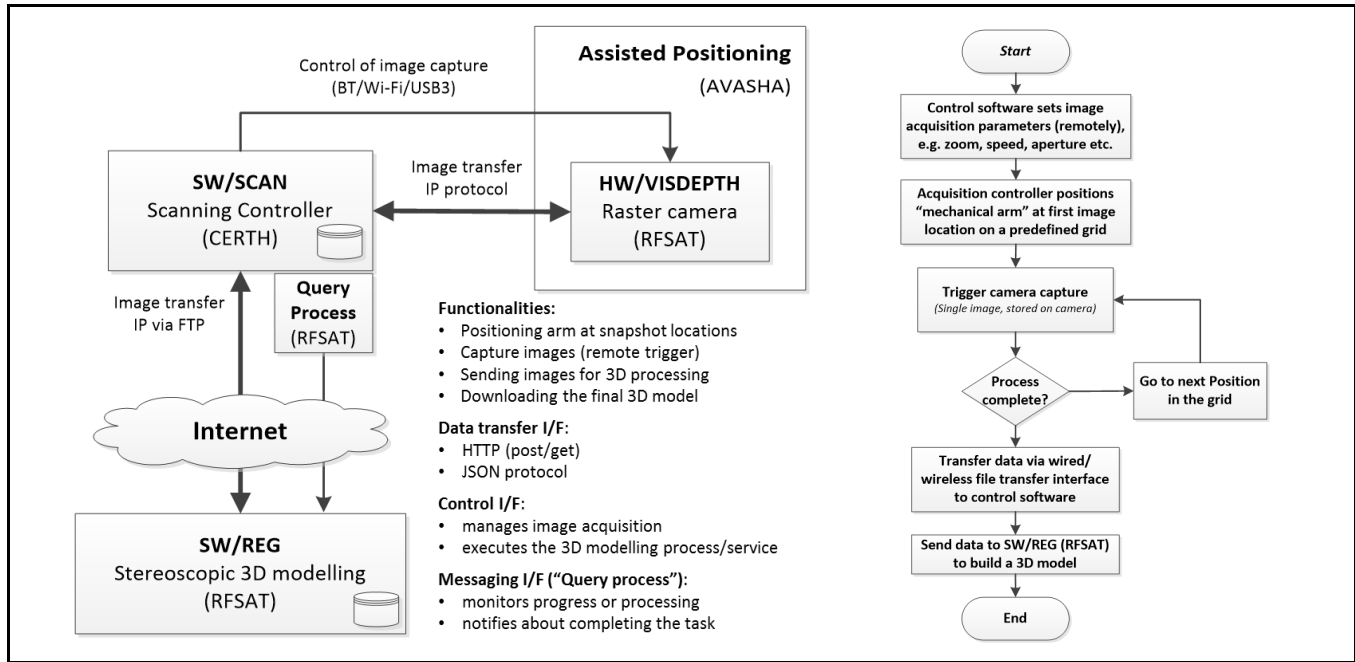
Photogrammetry or stereoscopic scanning is the technology of making depth measurements from raster photographs. It can be used for quick recording of vulnerable and inaccessible sites. Photogrammetry is also ideal way to obtain 3D information in situations where it is not possible to use 3D scanners (inaccessible locations, conflict zones), or when high-speed recording is required (scanning people, living organisms, liquids in movement). It is ideal for the recording of translucent surfaces like alabaster and marble. Due to the composite nature of the image capture, color and form can be extracted from the data. Until recently achieving highest resolution recording of surface for facsimile production and featureless, reflective and dark surfaces was not feasible.

However, re-cent software developments (e.g. by Pix4D Mapper, Autodesk ReMake and many other ones) it became possible through improvements to photogrammetry technology to become soon the dominant method for recording at risk cultural heritage in 3D and color. A special version of the photogrammetry is structured light scanning, whereby pre-defined shapes (commonly horizontal and vertical lines) are projected onto the object surface. By analyzing the change in line shapes from images captured by the camera, the shape of an object can be determined. However, methods like this do not offer high precision, which is dependent on projector and camera resolution as well as object complexity.

Photogrammetry has been used since the birth of modern photography in fields such as topo-graphical mapping, architecture and archaeology. The data can be recorded with commercially available cameras that capture multiple shots of the entire surface of an object. Close-range photography can result in high-resolution data. Basic processing is required in the field to ensure that no areas have been missed. Post processing is time consuming and hence suitable for applications where accuracy and precision of 3D scans predominates the speed of model creation.

#### 4. Implementation of automated 3D modelling sub-system

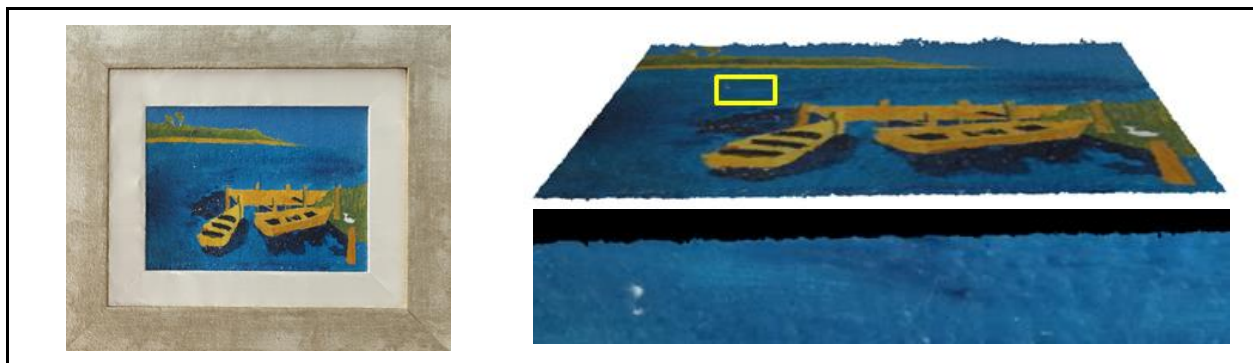
The photogrammetric 3D modelling provides not only the precise representation of the object geometry, but offers also a reference for positioning partial scans from other modalities. It also captures the object condition at a time that can be then aged artificially through digital simulation. The 3D modelling is done from several 50MPixel raster images taken with high-overlap (more than 70%) on a regular grid, thus providing high number of matching features among many images. The precise positioning and orientation of the camera in three dimensions (repeatable to single centimeters) is achieved by using a computer controlled mechanical arm. Images are then processed either locally (rough model only, due to a limited computational power of the rack PC) and/or using remote processing server where it can take advantage of the high processing power boosted by CUDA cores of the multiple Nvidia GTX 1080TI graphics cards. The functional diagram with scanning algorithm is shown in Fig. 2.



**Fig. 2.** Automated 3D scanning sub-system: flowchart (left) and processing algorithm (right)

#### 5. Experiments

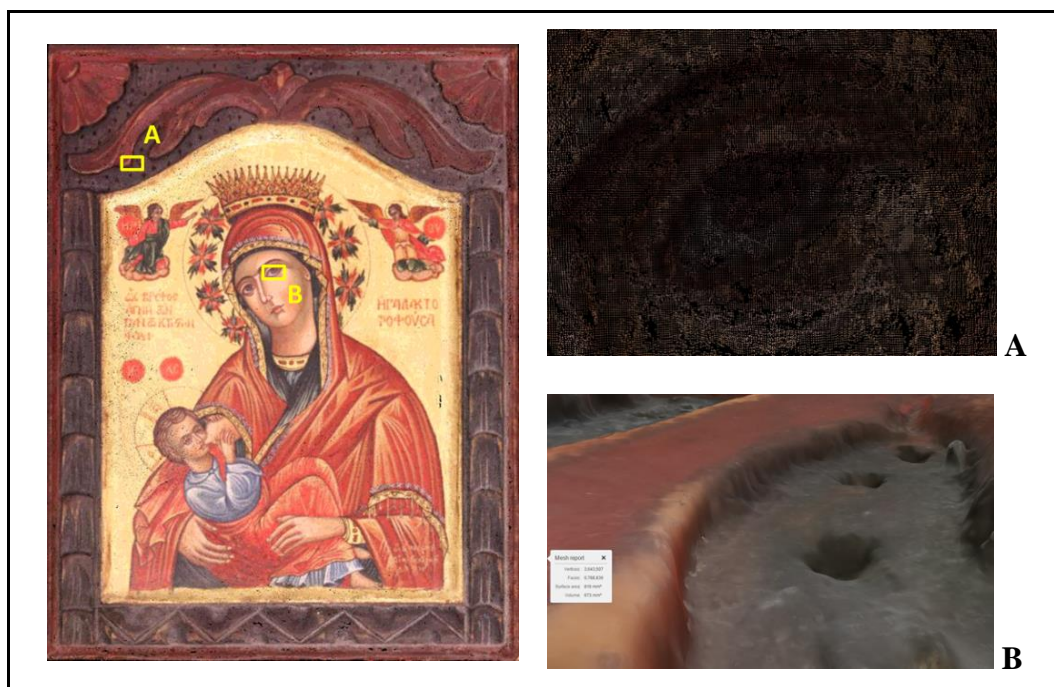
Several technology validations on different types of objects have been performed. The first one was a 3D scan of a small painting (30 x 40 centimeters) from the distance of 40 centimeters where consumer type hand-held 20 Megapixel SONY camera was used and model processed on a medium performance gaming type computer. In total 27 images were taken, from which a 3D model was produced. The painting exhibits degradation of its water-based paint surface, which can be clearly seen on the cross section of its 3D model. The accuracy of the surface variation was estimated around 0.1-0.4 millimeter. The processing time was 8 hours using an PC with i7 2.8GHz processing and single Nvidia GTX 970 graphics card.



**Fig. 3.** Results for test painting #1 with eroded water based paints



The next object was a replica of the Byzantine “lactans” icon (original dated 1784) showing Virgin Mary breastfeeding Jesus from the Museum of Thessaloniki. Here the highest resolution commercial camera Canon 5DS-R was used, which incorporates a 50Mpixel CCD sensor. A 20-years old icon has already shown signs of ageing with physical surface deteriorations and discolorations, thus being a suitable subject for high resolution analysis in both 2D and 3D. High resolution images allowed to achieve feature discrimination at accuracy reaching 57 micrometers (Fig. 4). A high-performance PC with i7-3.8GHz processor and dual Nvidia GTX1080 graphics cards allowed to perform the processing in less than 8 hours. A zoom into the selected features of the icon shows the precision of representation of both flat and recessed parts of the object to accuracy reaching 50 micrometers.



**Fig. 4.** Results of 3D modelling (right) of the Byzantine “lactans” icon (left) with 50Mpixel camera.

The next experiment was made on a life-sized bronze copy of San Giorgio statue by Donatello from the Museum of Bargello in Italy (original dated 1415) of approximately 1.5 meter in height, currently held at Opificio delle Dure in Florence. The result is presented in Fig. 5.



**Fig. 5.** The 3D scan of the copy of San Giorgio sculpture by Donatello (left) with visible erosions (right).

The object shows showing visible signs of erosions from environmental conditions and hence was chosen as test subject for high resolution determination of object surface deteriorations. The 44 raster images were used to produce a model with 3-million-point cloud with estimated accuracy at approximately ~0.25mm. This experiment, in addition to previous ones show the capabilities for this technology to produce 3D models with accuracies reaching the precision usually required by CH restoration facilities. In our experiments, we have used commercial photogrammetric software, such as Autodesk ReMake [8] (formerly known as Autodesk Memento) and ReCap, Pix4D Mapper Pro [7], AirTek Studio [10] and Agisoft Photoscan [9]. The performance and processing time varied significantly among those applications. After several attempts, we concluded that Autodesk ReMake and Pix4D Mapper were most suited to scanning the types of objects used in the SCAN4RECO projects (painting and icons, as well as metallic 3D objects up to the size of a life size statues) and conditions under which images were taken (indoor and outdoor with natural light). ReMake is an end-to-end solution for converting reality captured with photos or scans into high-definition 3D meshes. These meshes that can be cleaned up, fixed, edited, scaled, measured, re-topologized, decimated, aligned, compared and optimized for downstream workflows entirely in ReMake. It handles reverse engineering as support for design and engineering, for asset creation for AR/VR, film, game, art, for archiving and preserving heritage, digital fabrication or publishing interactive experiences on the Web and mobile.

ReMake plays well with Autodesk® ReCap 360, helping clean up, fix, edit, optimize and prepare the generated meshes from laser scans or photos for downstream use. ReMake simplifies complex processes since it was designed for users who require top-quality digital models of real-life objects but have little or no 3D modelling expertise. The early experiments with Autodesk ReMake in the SCAN4RECO project have shown several advantages, such as smoother edges and cleaner model mesh as compared to Pix4D Mapper, although the precision is significantly lower and models lack high object count, yet.

### 1.1.1 Comparison to other types of ToF scanners

- Laser scanners: the best ones reach 10 microns or better for small objects (usually up to 25cm in size).
- Microsoft Kinect 2.0 for Windows: evaluation tests proved that the best accuracy that can be achieved with the Kinect device is 3mm with the standard deviation of 3mm when scanning from 1.5 meters [14]. The 3D model creation using raster images achieves at least an order of magnitude better accuracy without any (potential) loss of valuable information!
- Structure.io Sensor [15]: allows to capture dense geometry in real-time, thus creating 3D models with high-resolution textures in seconds. However, models produced are of limited level of accuracy, below what is required for the SCAN4RECO project.

## 6. Conclusions and Directions for applied research

The price of laser scanners reaching (sub-)micrometer accuracy is too high, preventing wider adoption among CH restoration communities. Even cheaper solutions are more than the budgets foreseeing in SCAN4RECO project for such solutions. On the other hand, more affordable solutions compromise both in accuracy model complexity. Therefore, the photogrammetric technology appears to offer a good compromise between the achievable accuracy (@ 50 micrometers) and overall cost (12,000Euros including camera, workstation and 3D processing software). The applied research on combining raster images with rough depth information offers a potential for further improving the achievable accuracy.

The results from initial evaluation of photogrammetric technologies led to the following conclusions:

- Having a-priori knowledge of the precise camera position and following a fixed grid at known distance as well as increasing the overlap among images is expected to reduce border effects, reduce distance discrimination error and likely achieve an overall reduction of the number of faces.
- Increase of the number of point cloud more than 100 million and the faces count more than 10 million will naturally improve surface resolution, with rough estimate to reach better than 100 micrometers. To achieve such performance a dedicated processing system will be required to reduce processing time

to single hours (depending on the model complexity). The intended setup will employ multiple NVIDIA GeForce 1080 (SLI connected) graphics cards with high CUDA core count.

Relevant new research areas will further investigate:

- Use of depth data associated with raster images for (potentially) reducing borderline effects to negligible levels and overall resolution, hopefully leading to lower model complexity
- Extend the photogrammetric technology to penetrating imaging. First test will be made with combination of already owned thermal and visual imaging. Subject to positive results, investigation will follow to other sensors used by other project partners.

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## References

1. Smith, T.F., Waterman, M.S.: Identification of Common Molecular Subsequences. *J. Mol. Biol.* 147, 195--197 (1981)
2. May, P., Ehrlich, H.C., Steinke, T.: ZIB Structure Prediction Pipeline: Composing a Complex Biological Workflow through Web Services. In: Nagel, W.E., Walter, W.V., Lehner, W. (eds.) *Euro-Par 2006*. LNCS, vol. 4128, pp. 1148--1158. Springer, Heidelberg (2006)
3. Foster, I., Kesselman, C.: *The Grid: Blueprint for a New Computing Infrastructure*. Morgan Kaufmann, San Francisco (1999)
4. Czajkowski, K., Fitzgerald, S., Foster, I., Kesselman, C.: Grid Information Services for Distributed Resource Sharing. In: 10th IEEE International Symposium on High Performance Distributed Computing, pp. 181--184. IEEE Press, New York (2001)
5. Foster, I., Kesselman, C., Nick, J., Tuecke, S.: *The Physiology of the Grid: an Open Grid Services Architecture for Distributed Systems Integration*. Technical report, Global Grid Forum (2002)
6. Artur Krukowski and Emmanouela Vogiatzaki, „ UAV-based photogrammetric 3D modelling and surveillance of forest wildfires”, Workshop on “UAV & SAR: using drones in rescue operations”, ISA, Rome (Italy), 29th of March 2017.
7. Pix4D Mapper Pro (15th of March 2017): <https://pix4d.com/product/pix4dmapper-pro>
8. Autodesk ReMake (15th of March 2017): <https://remake.autodesk.com>
9. Agisoft Photoscan (15th of March 2017): <http://www.agisoft.com>
10. ArTec 3D Studio (15th of March 2017): <https://www.artec3d.com/3d-software/artec-studio>
11. Pix4D Capture (15th of March 2017): <https://pix4d.com/product/pix4dcapture>
12. NVidia GeForce cards (15/03/2017): <https://www.nvidia.com/en-us/geforce/products>
13. CUDA (15th of March 2017): [http://www.nvidia.com/object/cuda\\_home\\_new.html](http://www.nvidia.com/object/cuda_home_new.html)
14. Jeremy Steward, Dr. Derek Lichti, Dr. Jacky Chow, Dr. Reed Ferber, and Sean Osis “Performance assessment and calibration of the Kinect 2.0 time-of-flight range camera for use in motion capture applications”, FIG Working week 2015, “Wisdom of the Ages to the Challenges of the Modern World” Sofia, Bulgaria, 17-21<sup>st</sup> May 2015.
15. Structure.io sensor: <http://structure.io>