# Autonomous Aerial Systems in Service of Cultural Heritage Protection from Climate Change Effects

Artur Krukowski[1], Emmanouela Vogiatzaki[2]

[1] RFSAT Limited, Dublin, Ireland,
`Artur.Krukowski@rfsat.com`
[2] RFSAT Limited, Dublin, Ireland
`emmanouela@rfsat.com`

**Abstract.** The article reports on both past and ongoing work in such research projects as SCAN4RECO or ARCH, both funded by the European Commission under the Horizon 2020 program. The former one concerns multi-modal and multi-spectral scanning of Cultural Heritage (CH) assets for their digitization and conservation via spatio-temporal reconstruction and 3D printing, while the latter one aims to support better preservation of cultural heritage areas from hazards and risks, both natural and human-borne ones. Both projects have adopted co-creation methodologies to help pilot hosts (preservation institutions and cities) to save their cultural heritage from the effects of progressing climate change effects. This included developing disaster risk management frameworks for assessing and improving the resilience of historic areas to climate change and natural hazards. Tools and methodologies have been designed for local authorities and practitioners, urban population, as well as national and international expert communities, aiding authorities in knowledge-aware decision making. In this article we focus on presenting novel approaches to performing 3D modelling of object geometry using 3D photogrammetric methods using autonomous and automatic control systems for achieving very high model accuracies using consumer types of devices, attractive both to professions and hobbyists alike. We also present practically adopted approaches for remote monitoring of weather and climate effects in local and global scales as well as means of assessing possible negative effects that such natural climatic effects might pose on the level and speed of degradation of Cultural Heritage.

**Keywords:** 3D modelling; UAS; Cultural Heritage, Preservation.

## 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.

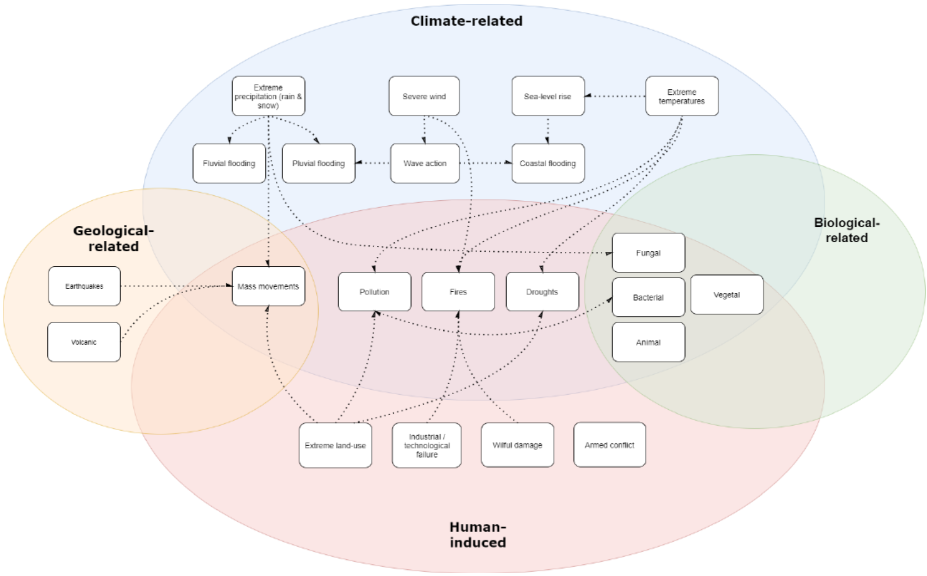


**Fig. 1.** Taxonomy of hazards to Cultural Heritage

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 con-trolled 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.

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.

The ARCH project [1] developed 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 ARCH project analyzed 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. ARCH project facilitates conservation by indicating spots/segments of cultural objects that are in eminent conservation need and require special attention, while suggestions are provided by a Decision Support System (DSS) about conservation methods to be followed.

## 2 SYSTEM ARCHITECTURE

The original SCAN4RECO offered 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 efficiently processes 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.

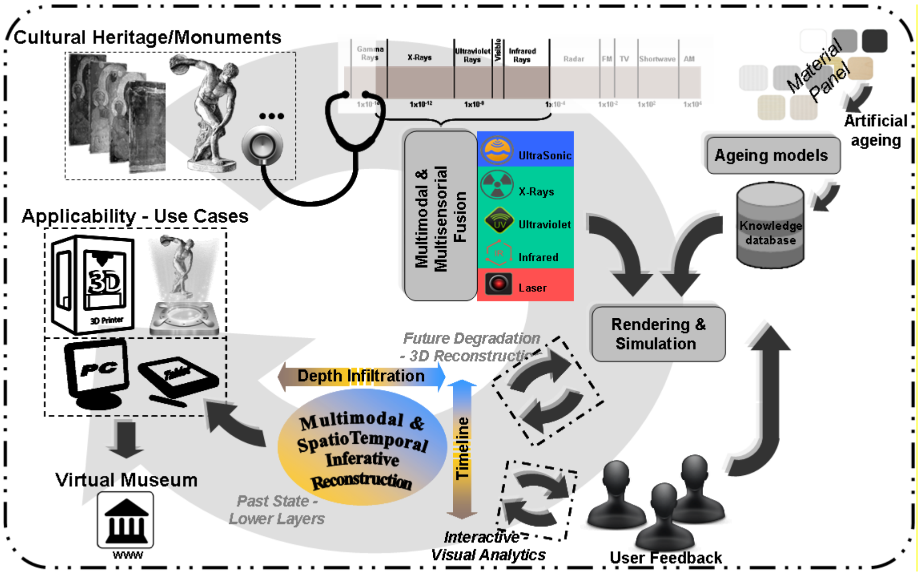


**Fig. 2.** Conceptual system architecture

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 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 rematerialized as a physical object - 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 multispectral 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 sur-faces 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, recent 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.

## 4 AUTOMATED 3D MODELLING 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 multiple Nvidia GTX 1080TI graphics cards.

## 5 SIMULATING AGEING EFFECTS

The H2020-ARCH project offers technology transfer from dealing with tangible objects to larger spaces whether they are buildings, statues, city areas, archeological sites [20] etc. As a result, technologies need to be extended from lab-type as in SCAN4RECO to portable, in many cases deployable on autonomous systems, such as aerial [19] ones able to capture objects well above the ground level and thus offer new way of analyzing their condition and assess risks of degradations, both due to natural erosion caused by natural environments, but also speeded up effects from Climate Change, natural events and/or human-borne incidents. Thus, it aims to strengthen the resilience of historic areas to climate change-related and other hazards by supporting decision makers in addressing the specific needs of those areas when formulating sustainable protection and reconstruction strategies. From technological perspective it offers means of determining current condition of tangible and intangible cultural objects, as well as large historic areas, gathered within an information management system for georeferenced properties of historic areas, structures, buildings, and artefacts, e.g. build material and existing protection measures. It includes an information management system for hazard data, captured via existing climate services and novel monitoring techniques leading to provision of simulation models for what-if analysis of the effects of hazards and potential measures, ageing and hazard simulation.

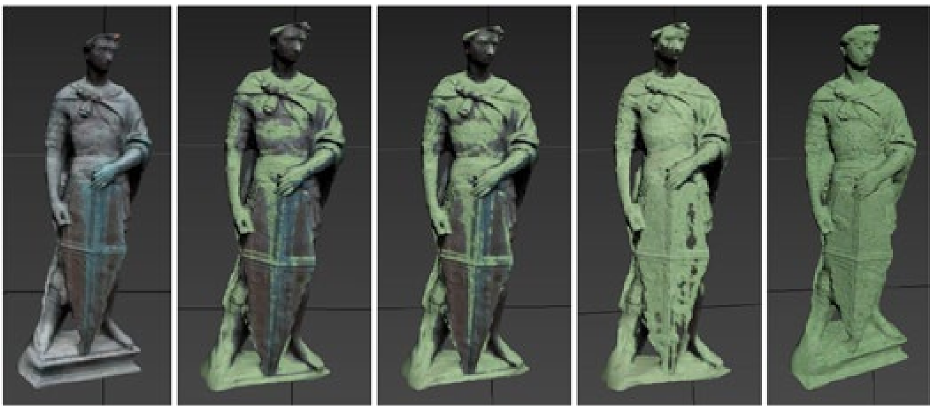

**Fig. 3.** Simulated ageing of a bronze statue of Saint Giorgio at 5-year intervals

As such it extends 3D modelling and ageing simulations from SCAN4RECO [21], shown on an example of Saint Giorgio statue in Fig. 3, adding means of monitoring climatic and weather changes that might have direct effect of degradations to cultural heritage objects.

## 6 AUTONOMOUS SCANNING AND MONITORING

Since 3D scanning and monitoring of large areas stretches beyond current capabilities of UAVs, new methods of operating large number of devices simultaneously over areas of interest, as suggested in Fig. 4, are proposed whereby initially flight control is linked to the pilot console (current legal requirement), though applied R&D is directed to fully relay autonomous mission control onto a dedicated embedded computer deployed on autonomous UAS.

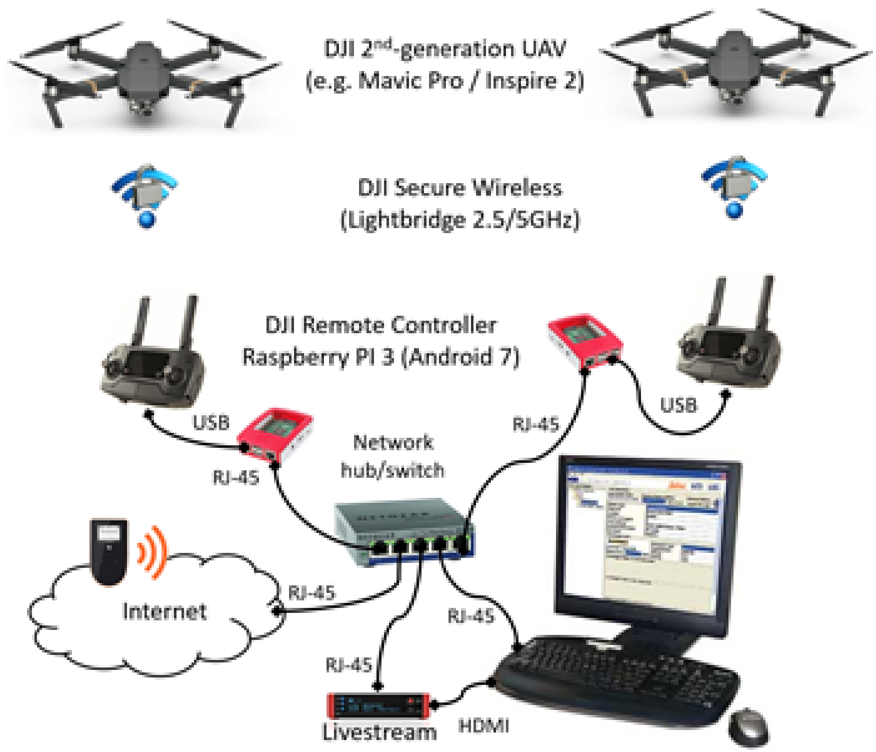


**Fig. 4.** Autonomous swarm UAS operation for 3D monitoring of large areas

## 7 EXAMPLE EXPERIMENTS

Several technology validations on different types of objects have been performed. The test showing the power of the technology was to 3D scan of a Saint Michael icon from Mount Athos monastery in Halkidiki (Greece). 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.

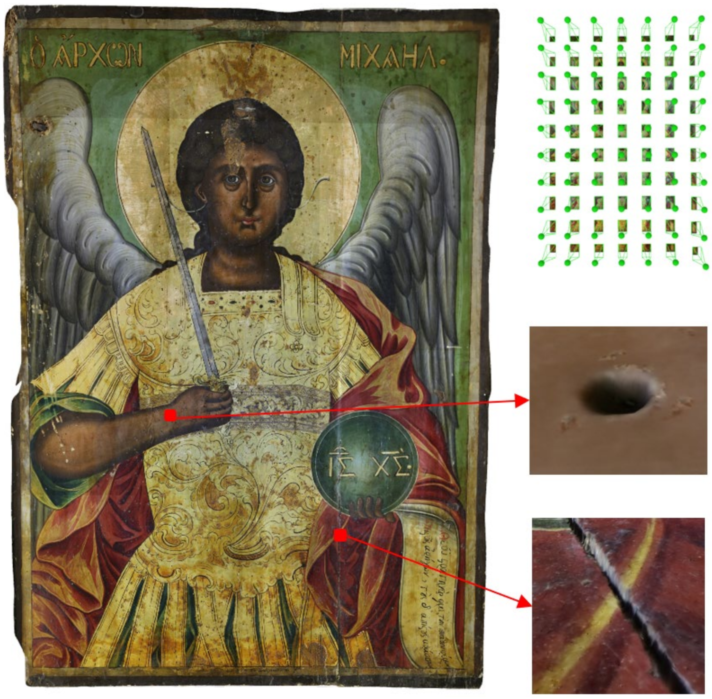


**Fig. 5.** 3D model (right) of Saint Michael icon (left) with 50MP camera

These experiments 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 publishing interactive for Web and mobile experiences. 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 precision is significantly lower and models lack high object count, yet.

## 8 EXTENDING FROM OBJECTS TO CULTURAL AREAS

Such a system will enable high level of autonomy in decision making in varying environmental conditions, monitored by e.g. a CIPCast-DSS system by ENEA that collects data from diverse sensors ranging from ground to aerial ones (Fig. 5), important during disasters or in cases where instant surveillance of large areas is required.

**Fig. 6.** CIPCast Decision Support System from ENEA used in ARCH project

## 9 CONCLUSIONS AND FURTHER WORK

In this article we summarized the main concepts behind use of new 3D scanning/modelling and simulated ageing of cultural heritage objects as proposed in the SCAN4RECO project, taking advantage of novel autonomous systems for monitoring large objects as well as large cultural areas of e.g. cities, excavations and/or disaster areas, as first proposed in the FP7-AF3 [18] project and currently extended in the H2020-ARCH [17] project. The vast amount of research performed in all three mentioned projects could only be signaled in this publication and therefore interested readers are suggested to explore online resources of publications, prototypes, demos and presentations available on the WEB portal of each of the mentioned projects

## ACKNOWLEDGMENTS

The research leading to these results has been partially funded by the European Union Horizon’2020 Research Framework under Grant Agreement N° 665091: SCAN4RECO, No. 820999: ARCH and No. N° 607276: AF3.

# References


1. H2020-SCAN4RECO project: https://cordis.europa.eu/project/id/665091
2. Smith, T.F., Waterman, M.S.: *Identification of Common Molecular Subsequences*. J. Mol. Biol. 147, 195--197 (1981)
3. 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)
4. Foster, I., Kesselman, C.: *The Grid: Blueprint for a New Computing Infrastructure*. Morgan Kaufmann, San Francisco (1999)
5. 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)
6. 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)
7. 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.
8. Pix4D Mapper Pro: https://pix4d.com/product/pix4dmapper-pro
9. Autodesk ReMake: https://remake.autodesk.com
10. Agisoft Photoscan: http://www.agisoft.com
11. ArTec 3D Studio: https://www.artec3d.com/3d-software/artec-studio
12. Pix4D Capture: https://pix4d.com/product/pix4dcapture
13. NVidia GeForce cards: https://www.nvidia.com/en-us/geforce/products
14. CUDA (15th of March 2017): http://www.nvidia.com/object/cuda_home_new.html
15. 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, 17-21st May 2015.
16. Structure.io sensor: http://structure.io
17. H2020-ARCH project: https://cordis.europa.eu/project/id/820999
18. FP7-AF3 project: https://cordis.europa.eu/project/id/607276
19. Krukowski, A. and E. Vogiatzaki, "*Autonomous Aerial Systems in Service of Cultural Heritage Protection from Climate Change Effects*", International Conference on Heritage Tourism, Cultural Heritage and Preservation (ICHTCHP'2021), Amsterdam, (The Netherlands), 21-22nd of January 2021 (https://panel.waset.org/conference/2021/01/amsterdam/ICHTCHP)
20. COST Action CA15201: https://www.cost.eu/actions/CA15201 and https://www.arkwork.eu
21. Artur Krukowski and Emmanouela Vogiatzaki, "*High Resolution 3D Modelling of Cultural Heritage*", 12th International Conference on non-destructive investigations and microanalysis for the diagnostics and conservation of cultural and environmental heritage (ART'17), Politecnico di Torino, 22-24th of November 2017, Torino, Italy