CHAPTER 19

Reconstructing Humans Using Photogrammetry

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Introduction

Digitalisation is a process that creates virtual 3D versions of real-world scenes and objects. Predominantly used for mapping in GIS science (Konecny, 2014), digitalisation technologies have increasingly become integral to many scientific disciplines such as archaeology (Drap et al., 2015), anthropometry (Weinberg et al., 2004), cultural heritage (Kingsland, 2020; Remondino, 2011), and forensics (Formosa, 2022; Gitto et al., 2020), allowing researchers to conduct detailed analysis – directly or remotely - with minimal risks of contaminating the real subjects.

Within the realm of digitalisation technologies, laser scanning technologies have existed for a few decades. However, they remain only within reach of professional entities with large budgets and expertise. Models created by laser scanners are superior in terms of structural integrity and resolutions (i.e., polygon counts), which requires large processing powers to modify and render (Foster & Halbstein, 2014). Recent developments in photogrammetry make it possible for virtually anyone with a camera device and access to commercial photogrammetry software (Stark et al., 2022) to use the technology. This enables idea generation and progress in low-scale projects such as in the case of educational bodies and individual artists. This chapter documents three low-scale projects using photogrammetry carried out at the SIntegraM MAKS Immersion Lab, University of Malta, led by Professor Saviour Formosa, in collaboration with Malta Forensics Lab and Malta Police Force, led by Inspector Charlot Casha. Data collection was assisted by forensics photographer Antoine Fenech. Data processing and dissemination was carried out by research officers Fabrizio Cali and Tram T. N. Nguyen at the SIntegraM MAKS Immersion Lab.

A common theme running across these projects is human-centred reconstruction. In the first project, we reconstructed a skull at the request of St Peter's monastery as part of a forensic project. In the second project, we reconstructed the face of a digital art student whose project was to create wearables. In the last project, we reconstructed the full body of Neil Agius – an Olympian swimmer – at the request of artist Austin Camilleri in his project to forge a 3-metre-high bronze sculpture. These constitute the category of close-range photogrammetry.

As opposed to far-range projects in which a semi-automated drone can be deployed, scanning close-range subjects requires manual execution of a camera or multiple cameras. This poses unique technical challenges (Samaan et al., 2013). Furthermore, progressing from an inanimate object such as a skull to a live subject (faces and bodies) raised the level of technicality required, especially given the constraints on equipment and budget. It is the aim of this chapter to demonstrate the feasibility of photogrammetry and detailed documentation for future attempts in replicating the process. General technicalities such as lighting, camera settings have already been discussed extensively in other literature (Foster & Halbstein, 2014; Linder, 2009). Instead, the chapter focuses on the unique aspects of each scanned subject and the technical solutions involved to achieve desirable results. The next section provides a brief description of photogrammetry techniques. Section 3 describes in detail the projects. Finally, we conclude the chapter with a discussion on future directions.

Photogrammetry: A brief overview

The word *photogrammetry* consists of *photo*, referring to light, *gram*, referring to drawing, and *metry*, referring to measurement. Photogrammetry is the science of measuring distance in three-dimensional (3D) space using photos. It falls within the category of remote sensing technology because measurements and distance analysis can be made without direct physical contact. The simplest example of photogrammetry is the way our brain infer depth, hence 3D perception, using image inputs from our two eyes (i.e., stereoscopic perspectives) (Linder, 2009).

In photogrammetry techniques, multiple photos are taken to capture every possible angle of a subject. A photogrammetry software employs sophisticated algorithms to calculate coordinates of an image feature (a pixel) relative to other features in 3D space – a process called triangulation. Triangulation dictates that each feature must be viewed from at least two different perspectives, hence one of the keys to successful 3D reconstruction is image overlapping. The suggested degree of image overlapping is approximately 50% or images taken from every 5-10 degree in angle (Foster & Halbstein, 2014), although this can vary depending on the characteristics of the scanned subject.

The fundamental principle of feature extraction and interpolation used in photogrammetry means that featureless objects (or parts of objects) are a major problem for a photogrammetry software. This also applies to glossy surfaces, as light can be reflected differently from different angles. These issues lead to incomplete or fractured models ('holes'), a problem we frequently encountered, especially in dealing with live subjects (see Project 2 and 3 for more details).

As mentioned earlier, photogrammetry in far-range projects, such as mapping an area, can be carried out by a drone with an automated function to take interval photos in a grid-like fashion. For close-ranged objects, manual execution of camera devices is often employed. Any human inconsistencies that cause image imperfections (e.g., blurring) can have detrimental effects on the working of photogrammetry algorithms, such as a complete failure in determining the target pixel in each image for triangulation processing. Furthermore, scanning a live subject introduces related, but different, kind of inconsistencies amongst the image sets, due to micro muscular and postural movement of the live subject. That means a given feature changes location between images, leading to double meshing in the final model. Our experience and that of others (e.g., Pesce et al., 2016; Samaan et al., 2013) have proven that systematic procedures to increase feature consistency is a critical contributor to the quality of the final models, among other basic technical considerations.

An ideal scenario of photogrammetry requires absolute removal of human inconsistencies. As such, full-scale automated and streamlined photogrammetry systems have been constructed. For example, the CultLab3D system uses robotic arms, conveyors, and multiple cameras to produce perfect 3D models of important archaeological artefacts (Santos et al., 2017). State-of-the-art scanning systems for full human bodies typically feature a camera rig with multiple high-quality cameras synchronised, so that any posture can be capture instantaneously and simultaneously at all viewpoints. Examples of such systems are the ESPER geodesic system (https://www.esperhq.com/), or the Botscan Neo (https://botspot.de/) which costs approximately $200,000. These professional systems are certainly out of reach for low-scale, educational, research-based, or independent projects, such as the ones carried out at our laboratory.

Nevertheless, several photogrammetry practitioners have attempted to achieve golden standards with ingenious low-cost solutions (Gitto et al., 2020; Iwayama, 2019; Stark et al., 2022, 2022). This is feasible because the quality of the final models is greatly determined by the skills and expertise in maintaining the core principles of the technique, namely consistent image overlapping degrees, lighting, image quality and standardisation. Successful results come from a systematic scanning process in which measures are taken to minimise human inconsistency. The following section goes into detail about the three projects carried out at our laboratory, the technical challenges each scanned subject posed and solutions to achieve satisfactory results.

Project details

In all three projects, we used a combination of a turntable and interval shooting modes. This setup ensured that camera angles were equally spaced and minimised micro movement of the camera as in the case of manual shooting mode (see Thomas et al., 2019 for a similar setup). Care was taken to balance the rotating speed, image clarity, and shooting duration. The final models were reconstructed using RealityCapture with an academic license.

Project 1: Reconstructing Beata Adeodata's skull

Background information

This project was a collaboration between our laboratory and Malta Forensics Laboratory, at the request of St Peter's Monastery, Mdina.

Beata Adeodata was born Maria Adeodata Pisani in Naples, Italy in 1806. Her father was a famous Maltese baron and her mother was Italian. She grew up in an aristocratic household and received a prestigious education from the famous Istituto di Madama Prota in Naples. After her father was sentenced to death due to his involvement in the Naples uprising, she moved to Malta at the age of 19. She became a nun at the Benedictine Community in St. Peter's Monastery at the age of 21. She led a modest and charitable life and was known to be a frail woman with physical and cardiac problems. She died in 1855 at the age of 48 and was buried in the crypt of the Benedictine monastery at Mdina. In 2021, a project to excavate her tomb was carried out. Apart from her skull, the rest of her skeletal remains were almost fully decomposed and unrecognisable. Her skull was reserved and displayed at the main chamber in the monastery. The purpose of this project was to archive her skull digitally and create a physical replica for further forensic research.

Technicality and procedure

A skull is a highly suitable object to photogrammetry due to its maneuverability and detailed featureful surface. One technical challenge of capturing the skull's entirety was to capture self-occluded parts such as the inner bone cheeks and eye sockets (Figure 1b).

Figure 1: a) Depiction of Beata Adeodata; b) Frontal view of the skull; c) Scanning setup.

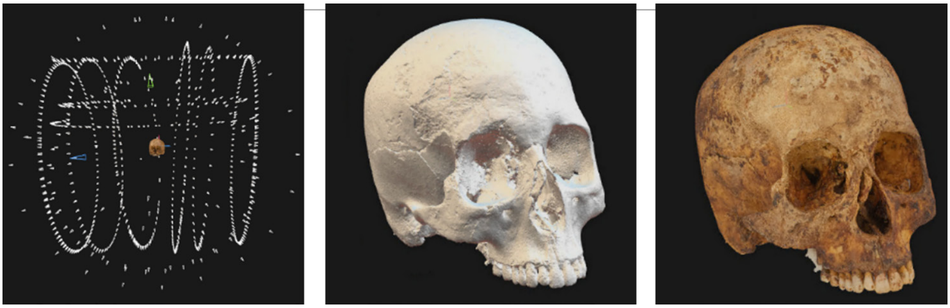
a) b) c)

To ensure balanced lighting, the skull and the turntable were placed in a reflective cave with lights surrounding the outside (Figure 1c). The skull was placed at four different positions (upright, sideways, inverted) to ensure every possible angle to be captured. At each position, the camera was set at three different heights to create enough coverage of self-occluded parts.

Result

Figure 2a shows the final model with camera positions estimated by the software. The model was impeccably reconstructed in RealityCapture in the first run with all self-occluded parts captured (Figure 2b), suggesting that our scanning setup was adequate. The textured simplified model is shown in Figure 2c.

Figure 2: 3D model of Beata Pisani's skull. a) Camera positions, b) Solid mesh, c) Textured mesh



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Remarks

The result of this project highlighted the importance of systematic shooting in photogrammetry techniques, among other basic technical arrangements such as lighting and camera settings. Although there exist post processing solutions that can be applied to problematic datasets (for example, manual alignment using control points), a high-quality dataset can yield a quick and successful model using RealityCapture software (under an hour in this case). The result of this project (i.e., the 3D replica of the skull, available by request at our laboratory) can be used to conduct further forensic research such as facial reconstruction of Beata Adeodata. A topic brought to our attention was that all existing depictions of the nun were largely idealised (Figure 1a), and the monastery expressed their wish to recreate her face, humanising a real religious figure. This is a real possibility which has been extensively studied in the domain of forensic facial reconstruction literature (Wilkinson, 2004). The resulting 3D model can enable experts in this field to attempt reconstruction both by traditional clay sculpting techniques (Manley et al., 2002) and computerised modelling (Lindsay et al., 2015).

Project 2: Reconstructing a face

Background information

Gabriel Joseph Chetcuti is a digital art student specialising in sculpting wearable face masks using thermoplastics for his dissertation titled Cyclical Constructs. He approached our laboratory to help create a 3D model of his face, to be used in his dissertation project.

Technicality and procedure

As mentioned in the introduction, reconstruction of a live subject is challenging in photogrammetry because of natural micro movement. This has led to the creation of camera rigs that capture 360 degrees viewpoints simultaneously. Without such equipment, the subject must maintain static during the whole shooting period. We fine-tuned the setup so that the shooting duration was as quick as possible, which was more than one minute. One technical challenge of this project was that the skin around the nose was featureless and semi-glossy. To overcome this, we placed face markers over the nose to improve feature detection (Figure 3a). Because we aimed to capture the shape of the face only, one camera set at one height was used.

Result

Figure 3: a) Markers were placed on Chetcuti's nose to improve feature detection within this area, b) Final mesh consisted of 3.5 million polygons, note slight deformation around the top part of the nose, c) Final textured mesh. (with permission from Gabriel Joseph Chetcuti).

Figure 3: a) Markers; b) Mesh; c) Textured Mesh

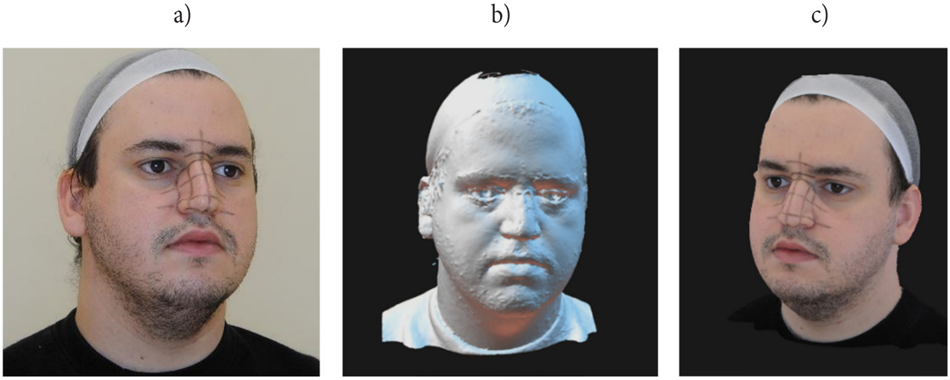

Figure 3b showed the untextured mesh of Chetcuti's face. It was evident that the lack of features around his nose was not completely compensated by the face markers. RealityCapture detected marked lines sufficiently to preserve the shape of his nose but failed to estimate the surface between the lines, resulting in some deformations. Nevertheless, the result was satisfactory for the purpose of his project.

Remarks

The project demonstrated how 3D scanning can be made accessible in educational settings. The process was quick, and the result was reasonable to assist students in pursuing their academic projects.

Project 3: Reconstructing Neil Agius's whole body

Background information

Neil Agius is a Maltese former Olympic swimmer and an anti-pollution activist. On 30 June 2021, Agius swam a total of 125km from Linosa to Gozo in over 50 hours, breaking the world's record for the longest non-stop unassisted swim in open water. The record was a symbolic achievement to raise awareness of sea pollution, expressed by his team "If Neil can swim for two nights and two days, no stopping, no getting out of the water WE CAN ALL pickup six pieces of plastic and do a few reps of exercise." (Times of Malta, July 2021).

One month after this nationwide famous event in August 2021, artist Austin Camilleri embarked on a grand project to forge a 2.6 metre and 266kg bronze statue of Agius as the centre piece for his solo exhibition LE.IVA Anger is a lazy form of grief (Martinez et al, 2022). Camilleri sought to finish the project within six months, so that the statue could be exhibited while Agius' campaign messages were still fresh in the public consciousness. This was an extremely ambitious goal, given that a normal process to cast a bronze statue of this scale, especially of a human subject, can take years. To realise this project, Camilleri approached our laboratory to create a 3D model of Agius to accelerate the process of making the cast.

Technicality and procedure

With the same challenges posed by scanning a live subject (see Technicality and procedure, Project 2), scaling up a scanning procedure from a small region (e.g., face) to a whole body brought about new challenges. In terms of the subject, Agius had to maintain a still whole-body posture throughout the process. In terms of technical setup, we had to cover his whole height while maintaining an adequate degree of image overlapping with minimal shooting time. The longer it took to scan, the more posture micro movement would be introduced. For this reason, in the initial scanning session, we opted to use video shooting with the camera revolving around the subject in multiple loops distributed according to his height. However, the initial result was not adequate due to the instability of the chosen posture and the low quality of images extracted from a video

We decided to return to the method of using a turntable and interval shooting setup, which required multiple cameras for height coverage. We were able to arrange these additional cameras through the help of the Malta Forensics Laboratory. Forensic photographer Antoine Fenech oversaw the setting up and monitoring of the cameras (see Figure 4 for the setting up process). Because these cameras have different sensors and lenses, care was taken to ensure that white balance was consistent across all cameras. Fine-tuning the setup took us approximately four days.

Figure 4: Scanning setup overseen by forensic photographer Antoine Fenech

Similar to the face of Chetcuti (Project 2), the featureless whole-body skin was a major issue in photogrammetry, to which we again resorted to using body markers (Figure 4).

Result

Figure 5: 3D model of Neil Agius. a) Camera positions, b) Solid mesh, c) Bronze statue

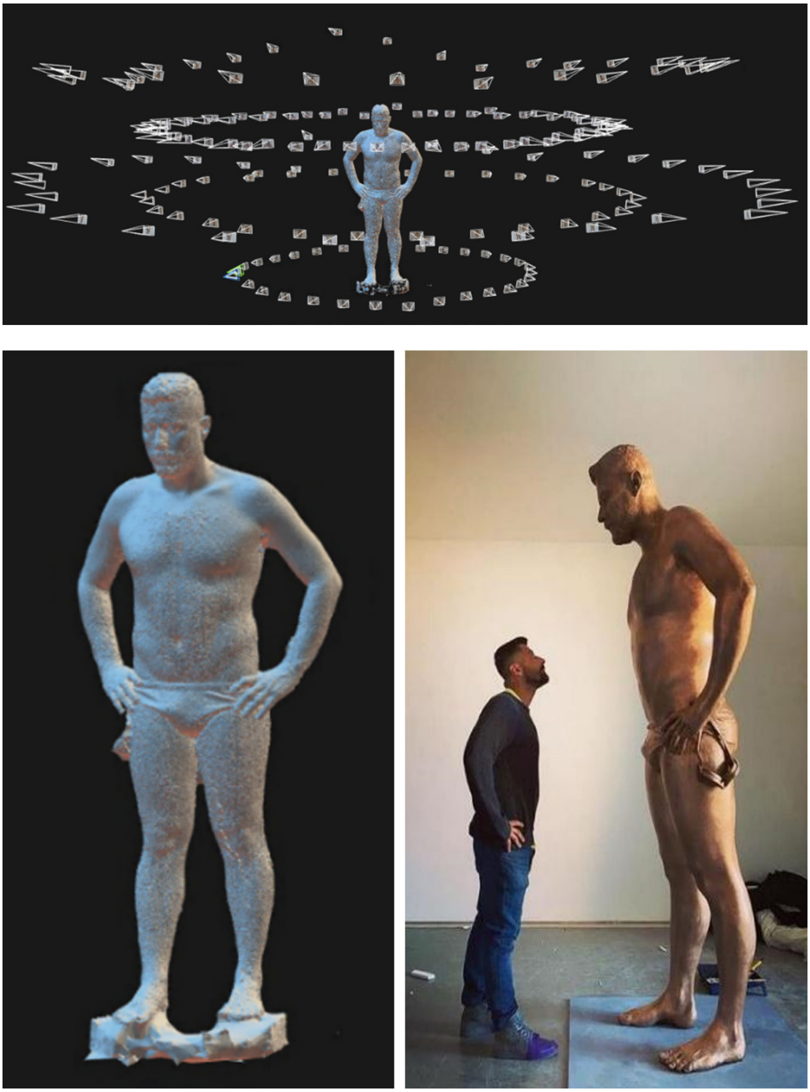

Figure 5 shows the model from the final scanning session using a turntable and multiple cameras set in interval shooting mode. We had to find a good posture for him to maintain balance and stillness on the turntable, this choice resulted in an adequate model (Figure 5b). Although this is a limitation of our setup, the chosen posture has a personal meaning to Agius, as he stood meditating at the ocean before embarking on his strenuous swim. The artist used this scan to 3D print model, enlarge and detail it manually in wax before the lost wax bronze casting process. Figure 5c shows the exhibition of his statue at Spazju Kreattiv in Valletta in February 2022, exactly six months later, as artist Austin Camilleri aimed for.

Remarks

Reconstructing the whole body of a live subject is the ultimate challenge to those who pursue close-range photogrammetry. The project proved that constraints on time, budget, and equipment can often lead to innovative solutions. It also confirmed that photogrammetry is a feasible technology to use for small-scale independent projects. To our satisfaction, this work has become a useful tool to assist contemporary artists like Austin Camilleri, as well as Neil Agius's effort to raising awareness about an urgent global issue. In Agius's own words, "I was taken aback by this feeling of knowing that this statute, this legacy will be here long after I'm gone. It also hit home that the choices we make to protect our sea, and our planet go well beyond us. The choices we make today will have an impact on our children's future and on our planet - a legacy that will last beyond our lifetime." (Facebook post, February 2021).

Future directions and conclusions

One important aspect that we did not control throughout these projects is the degree of accuracy of the models in relation to the actual physical subjects they represent. As mentioned before, because photogrammetry is a remote sensing technology, unlike laser scanning technology, structural accuracy depends greatly on the combination of various factors including the quality of the inputs, the systematic procedure, and the algorithm employed by photogrammetry software. Therefore, whenever structural accuracy is essential, it is advisable to employ laser scanning or combine laser scanning and photogrammetry. The latter option can maximise the strengths of both technologies to produce models with high structural fidelity provided by laser scanning inputs and high-quality textures provided by photogrammetry images. Having said that, recent research has shown that the margin of error can be reduced drastically in photogrammetry with the right setup (deviations under 1mm Katz & Friess, 2014; deviations ranging between 0.01 and 0.02mm Pesce et al., 2016).

Secondly, our current available equipment limits the types of posture to be captured successfully and requires the scanned subjects to maintain stillness for the whole scanning period. Such limitations can be overcome by using extensive camera rigs as seen in large funded commercial projects. We can achieve this standard to a certain degree with lower budget requirements by using inhouse designs and low-cost but more versatile camera modules such as the Raspberry pi camera modules (refer to Iwayama, 2019 for such an attempt). This would semi-automate and streamline the process, allowing any possible posture to be captured instantaneously.

In conclusion, the projects described in this chapter demonstrate that photogrammetry is a viable solution to reconstructing inanimate and live human 3D models. It is especially compelling for those who have constraints on budget and available equipment. The final products can enable further research without contamination of the original subjects (Project 1), as well as extend artistic boundaries and provide added social values for such endeavours (Project 2 and 3). Future research developments in photogrammetry setup, for example, incorporating the element of portability in a camera rig, would open the possibility to work on projects in which scanned subjects cannot be moved, for example, large collections of archaeological artefacts or onsite forensic evidence.

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EPILOGUE

Space within Space

Timmy Gambin

To speak of a ‘digital world’ project is the idea of two parallel realties – the ‘real’ world and the digital or virtual ones. In 2022, this distinction is not only erroneous but also very dangerous. Erroneous because the real and the digital-virtual worlds are so intricately linked that it is impossible to imagine a modern world without the plethora brought about by simply translating basic daily staples such as images, words and music into a series of ones and zeroes. Dangerous because decisions taken today impact future generations and, as this volume clearly demonstrates, the future can be a better place with the benefits brought about by the digital revolution. But what about making the invisible visible?

One small but very tangible example was revealed during the recent COVID pandemic. This example stems from the fields of education and cultural heritage – specifically underwater cultural heritage. This example does not just refer to the technologies specifically developed, adapted, or simply utilized specifically to manage and fight the pandemic. Just as with many sectors, the pandemic was very tough on the cultural heritage sector. Museums were shut down, staff laid off and much-needed fieldwork and restoration projects postponed or cancelled completely. A situation that at first glance seemed completely hopeless, presented a series of opportunities.

- Closed museums provided the perfect opportunity to scan and digitize objects and collections that are otherwise untouchable. Untouchable because they form the core of collections and are one of the reasons why people pay an entrance fee. Many museums, including those run by Heritage Malta, undertook the scanning and digitization of objects that are displayed as well as others from the reserve collection. These were initially done using an ARTEC Leo handheld scanner with data processed on Artec’s propriety software ARTEC Studio. Scanning was executed on site, data transferred online. Data processing took place overseas where a team member was caught in lockdown and subsequently uploaded onto Sketchfab, where a researcher annotated the objects (remotely) before making these available to the public. Besides making objects accessible via the world wide web, Heritage Malta produced over 500 digital models – a digital record that could be used, shared, admired and enjoyed remotely.

- If people cannot go to the sites, then it is imperative that heritage managers take the site to the people. Gozo's coastal towers and gun batteries were all scanned and shared during the pandemic – enabling people to explore these fortifications from the comfort of their home. 3D photogrammetric surveys were carried out using a DJI Mavic pro drone. Images were obtained during repetitive circular flights around the structures as well as cross lines to ensure overlap. Data processing was done using Agisoft Metashape and annotations done on Sketchfab. These towers and gun batteries are exposed to severe weathering and are periodically restored. The simple approach to 3D photogrammetry provides heritage managers and conservators with an easy and affordable solution for recurrent surveys that serve as baselines for future conservation interventions and management plans.

- Underwater archaeological sites are only accessible to those qualified in SCUBA diving. Deep water archaeological sites are reachable to an exclusive group of highly trained and experienced individuals qualified in technical diving. However, there should be no distinction between sites on land and those underwater – at whichever depth these may be situated. To overcome the barrier that is the water column, Heritage Malta and the University of Malta combined forces to create and launch underwatermalta.org – a virtual museum that showcases 20 underwater sites. This initiative is in line with UNESCO's best practices as propounded in its 2001 Convention for the protection of underwater cultural heritage: state parties are to "encourage responsible and non-intrusive public access to underwater cultural heritage in accordance with Articles 2.5 and 2.10 of the Convention." To populate the museum, teams of technical divers developed innovative recoding techniques that enabled the production of 3D photogrammetric models of sites that range from a cold war airplane to a 2700-year-old shipwreck. Site sizes ranged from 12 meters to 150m long and depths varied from 38m to 115m deep. Visitors to the virtual museum can not only experience the sites via standard videos and photographs but also through interactive 3D models and virtual reality.

- One of the most state-of-the-art methods of communicating the underwater world to a 'dry' audience in the post-pandemic world is through videos shot in 3600 with specialized cameras such as the Boxfish and the Insta360 with an Easydive housing. Heritage Malta recently launched its Dive into History 360 outreach campaign. Audiences are given short briefings about the sites they are about to experience. Members of the audience are then asked to put on VR headsets through which they can watch an omnidirectional (and annotated) video of a particular wreck site. Following the video, the audience engages with speakers

> in what is in essence an audience-led discussion. In the long run 3600 videos will be made available to a broader audience with educators able to download these videos and share them with their own audiences.

Over recent years, several tools for data acquisition, processing and sharing have become available and are radically changing the ways we communicate with audiences interested in underwater cultural heritage. Although underwater cultural heritage is often considered to be out of sight and therefore out of mind, it is through spatial and digital data that the underwater world has become shareable and available to a global audience.