THE 3D RECONSTRUCTION OF THE SANSEVERO CHAPEL ANATOMICAL MACHINES: A GEOMATICS CHALLENGE

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ABSTRACT:

This work presents the results of a geomatic survey conducted on the Anatomical Machines within the Sansevero Chapel in Naples, Italy. These anatomical artifacts have the unique characteristics of being upright standing skeletons with nearly intact circulatory systems. Previous research revealed that the intricate vascular systems, once believed to be natural, are instead elaborate reconstructions made using materials such as beeswax and dyes.
In response to the lack of metric data of these models, a series of geomatic surveys has been conducted to create the Machines' 3D models. This study discusses the theoretical and practical challenges associated with surveying these complex and fragile artifacts, emphasising the need for accurate extraction techniques to overcome the limitations imposed by the wooden cases in which they are encased. Two distinct approaches were used: a photogrammetric reconstruction and a laser scanning survey to overcome some logistical difficulties encountered. Despite the challenges, the 3D models' analysis gave satisfactory results.
This work addresses the palaeopathological and anatomical questions related to the Anatomical Machines by leveraging non-invasive geomatic methodologies, shedding light on the complexities of surveying historically significant artifacts and aiming at further establishing a valuable foundation for improving these modelling techniques.

1. INTRODUCTION

Inside the *cavea* of the Sansevero Chapel, located in the old town of Naples, two wooden cabinets with glass door exhibit the Anatomical Machines. These models, a male and a female, are two upright-standing skeletons surrounded by their almost perfectly preserved circulatory system. There was also a newborn baby with its placenta and unsevered umbilical cord lying at the mother's feet, but it was stolen in the second half of the 20th century.
The original models, protagonists of legends and stories, were commissioned by Raimondo di Sangro, Prince of Sansevero (1710-1771) in the second half of the 18th century to the Sicilian physician and anatomist Giuseppe Salerno (1728-1792). Moreover, Rosanna Cioffi (Cioffi, 2015) demonstrated that Giuseppe Salerno was on his way to Bologna when he met Francesco Bonocore, physician of King Charles III. Based on their correspondence, it is believed that Bonocore introduced Salerno to the king and to Raimondo di Sangro, who then purchased the skeletons for 50 ounces.
The two models reveal the network of blood vessels in such detail and accuracy that for a long time it was believed that the reproduced circulatory system was natural. Indeed, Carlo Celano asserted that the machines were made "through injection" (Celano, 1792). Furthermore, according to an account from Benedetto Croce, two servants were targeted with death by injection of embalming substances into their blood vessels, thus providing the skeletons for the "Machines". It should then be noted that the only human remains are the machine bones, whose sex can only be determined through anthropometric measurements on the skeletons themselves.
Among the most widely used techniques used for the definition of the composition of such artifacts, scanning electron microscope (SEM) analysis and Fourier transform infrared spectroscopy (FTIR) (Bayarı et al., 2020; Sciatti et al., 2023) are generally employed.
In 2007, through SEM and FTIR analysis, Dacome and Peters (Dacome & Peters 2007) demonstrated that the blood vessels have a core of metal wire twisted with fibres and coated with pigmented waxes. Nevertheless, no mention was made of the nature of the metal wire or the fibres used. The authors focused their studies on the components of the vascular system sampling vessels in different areas, without determining the shape and size of each individual component. Furthermore, recent investigations assessed that, while the bones are authentic, the blood vessels are extraordinary artifacts that also might reproduce some congenital malformations (Della Monica, M. et al. 2013), (Di Michele, S. et al., 2015). However, no metric survey has ever been conducted to obtain the Machine's digital copies until 2022, when an agreement between the Sansevero Foundation and the Department of Motor Sciences and Wellness of the Parthenope University of Naples allowed for a series of geomatic surveys to be carried out; thanks to these surveys, the 3D models of the two Anatomical Machines have been finally reconstructed.

1.1 Related works

Several research demonstrated the effectiveness of non-invasive techniques such as photogrammetry and laser scanning in

documenting historical and fragile artifacts. The ability of photogrammetry to accurately capture and reconstruct three-dimensional representations of artifacts, coupled with the precision and detail offered by laser scanning, has revolutionized the approach to artifact preservation and documentation. Several studies highlighted the accurate measurements and 3D image-based modelling of cultural heritage objects using minimal camera networks (Sapirstein, 2016; Alsadik et al., 2014). Inzerillo has also utilized photogrammetry for the virtual reconstruction of the Salinas archaeological museum (Inzerillo, 2017). Furthermore, Porter et al. (Porter et al., 2016) compared photogrammetry and reflectance transformation imaging techniques for the imaging of Paleolithic art objects, demonstrating the efficiency of portable and low-cost solutions.
An interesting study conducted on human fossil records proposes a low-cost hardware implementation for digital acquisition, which has been tested on the Neanderthal skull Saccopastore 1 (Buzi et al., 2018). They implemented a semi-automatic procedure by the introduction of an automatically rotating platform based on the Arduino UNO™ microcontroller, and further evaluated the performance and the resolution of the acquisition by comparing it with the CT-Scan of the same specimen through the calculation of their shape differences. Another study exploited the same task by relying on Structure from Motion single camera photogrammetry, reaching a scale error of less than 1mm (Lauria et al., 2022).
Some more recent works gave a substantial contribution towards the survey techniques of historical artifacts. Li et al. presented the extraction process of human bone relics at the Shenna Ruins in China based on the integration of the laser scanning data (Li et al., 2022). They achieved a reduced human intervention and destruction on the site compared with the traditional archaeological human bone packaging and extraction process. Moreover, the high-precision and high-resolution 3D digital models allowed for the restoration and further protection of cultural relics, and the point cloud resulted useful for establishing archaeological archives and conducting biological archaeological research on human bones.
An interesting digitalization workflow, applied to four Sumerian civilization masterpieces preserved in the British Museum, was employed using different sensors and technologies, such as close-range photogrammetry and CMM (Coordinate Measuring Machine) arm scanner (Patrucco et al., 2023). Such techniques were used to create dense and accurate 3D point clouds with the aim of achieving maximum geometric and radiometric quality for the digital replicas of the museum artifacts. The exploitation of a photogrammetric survey based on a pipeline of Structure from Motion (SfM) and Image Matching (IM) was highly appreciated for its cost perspective, with a system accuracy of 0.038 mm for Non-Contact Measurement.
A comprehensive 3D survey and digitization approach to capture the intricate details of historical fragile artifacts to facilitate a Scan-to-3D model-to-XR process can be adopted as demonstrated in (Banfi et al., 2023). They used multi-scale photogrammetric techniques, both aerial and terrestrial, to capture the entire context, encompassing the artifacts, archaeological sites, and historical structures at a high resolution; different lenses for capturing larger surfaces and finer details ensured the acquisition of diverse graphical outputs, such as coloured point clouds and mesh models at different resolutions. The results demonstrated the successful generation of integrated 3D data that provided architectural, archaeological, and paleoanthropological insights.
Focusing on the specific case of human body 3D reconstructions, medical studies gave a fundamental contribution to the topic. For example, an ad-hoc photogrammetric setup was employed to produce digital 3D models of 8 dissected specimens of regional anatomy, obtaining anatomical models authentically and precisely representing the original specimens (Petriceks et al., 2018). Due to their high level of detail, the resulting 3D models were used for teaching by making them interactive, thus allowing to enhance the approach to anatomical education. In this field, an interesting work compared three different techniques: 3D scanning, Micro Computed Tomography and Photogrammetry for inspecting the number of faces of polygon mesh and texture quality (Edelmers et al., 2022).
Furthermore, photogrammetry applied to formalin-fixed or plastinated specimens models allowed to obtain detailed anatomical photorealistic 3D digital models by relying on the accurate caption of fine surface texture data; moreover, making the acquisition in an open-plan laboratory classroom with studio lights and spotlights at different orbital planes (Titmus et al., 2023) allowed for the successful 3D models reconstruction of the heart and brain.
An interesting review made by Lussu and Marini analyses the methodological aspect of 26 different human-focused surveys, investigating the performances, the software and the technical implementation used for skeletal anthropology. All these studies employ the close-range digital photogrammetry as the main technique (Lussu and Marini, 2020).
Another review by Silva et al. further demonstrated the reliability and accuracy of photogrammetry in estimating the sex for human identification using dry skulls, proving the potential of non-invasive methods in capturing intricate details of historical artifacts without causing damage. Moreover, the assessment of risk of bias in the selected studies offers valuable insights into the methodological considerations needed to ensure the reliability of this kind of approaches (Silva et al., 2023).
However, some limitations need to be considered when performing this kind of survey (Fau et al., 2016). In the specific case of the Anatomical Machines here presented, issues with the scaling procedure and in particular with the Machines' position had to be faced. In fact, both the man and the female are within the wooden case, and whilst the female is supported by a stand, the male is fixed to the wall, thus obviously limiting the survey process from a physical point of view. This study aims then at obtaining interesting anatomical evidence of the cases studied and at the same time at highlighting the connected challenges; the final scope is to contribute and support further research and optimization, which are necessary to address the limitations and to improve the accuracy and efficacy of these methods towards the improvement of cultural heritage preservation policies.

2. MOTIVATIONS & CHALLENGES

There is a lack of written documentation regarding the early history of anatomical machines, which makes it difficult to determine how they were really made. Only a few medical studies have been published on the topic so far, and they only partially cover the matter. In 2013, Della Monica and coworkers (Della Monica et al., 2013) studied the surface anatomy of the heart and great vessels in the two models. This study demonstrated the normal size and position of the heart in both models and reported some anomalies, such as the anatomical variations in the vessel branching from the aortic arch, the venae cavae etc.; furthermore, they described a pulmonary atresia in the female model and a single stem of the coronary arteries in the male one. Additionally, (Di Michele et al., 2015) described a little hole in one of the ventricular walls in the same model, which was eventually caused by a myocardial infarction. Also, there is no doubt about the genuine osteological nature of the bones that was clearly assessed in (Cioffi, 2015). However, as far as the authors are concerned, no archaeological or anthropological analyses have been carried out so far. As previously mentioned, the

Anatomical Machines might be considered very complex artefacts, especially when it comes to the survey process. In fact, their fragility prevents their extraction from the wooden cases in which they are preserved, thus posing hard constraints in the acquisition phase and in the consequent production of a complete three-dimensional reconstruction.

Moreover, a significant portion of the circulatory system has been created using a metal wire coated with coloured wax and silk fibers: the wire section of only few millimetres poses a great challenge from a morphological perspective, due to the high level of detail required.

The operational challenges of the survey together with the need of detecting objects with sub-millimetric dimensions require for the use of effective geomatic extraction techniques to obtain accurate 3D models (Marshall et al., 2019). For this reason, two different approaches in different steps have been employed for this survey: a photogrammetric one, which only relies on optical cameras, and a laser triangulation, which combines the use of a laser and a camera. Photogrammetry allows for the reconstruction of the 3D model of an object by processing images or video sequences reproducing it from different perspectives (Bellavia et al., 2022). The scientific analysis based on strict equations, field measurements, and mathematical models enable in fact the transition from the 2D space of images to the 3D space through the phases of acquisition, orientation, interpretation, and restitution (Yilmaz et al., 2007). The accuracy of the results is closely related to the quality and definition of the images, as well as the geometric configuration of the photographic shots. Due to the constraints imposed by the museum management and the presence of wooden boxes, the previous two requirements cannot be fully met, and this undoubtedly produces an incomplete and locally noisy reconstruction.

The purpose of this study was to address the palaeopathological and anatomical enigma represented by these two models, as well as to analyse previous diagnostic hypotheses and exploit geomatic acquisitions to conduct non-invasive analyses. Therefore, the use of geomatic techniques for this problematic case study represents both a challenge and an opportunity to improve the achievable results.

3. MATERIALS AND METHODS

As previously mentioned, two different survey approaches were carried out on both the Anatomical Machines: the former based on a photogrammetric approach and the second one based on a laser scanning acquisition.

3.1 Photogrammetric acquisition

During the photographic data acquisition a halogen spotlight was used to indirectly illuminate the Machines, along with two parabolic projectors equipped with calibrated bulbs with a colour temperature of 4000 °K.

On the 15th June 2021 an initial photogrammetric survey of both the Anatomical Machines was made, using a Nikon D800E (CMOS sensor with 36.3 megapixel and 4.8 micron pixel size) full-frame reflex camera equipped with a 60 mm lens. The use of such a lens was obliged by the fact that the minimum distance from the machines could not be less than 50 cm and that the views were necessarily limited by the presence of the side walls of the two glass showcases, which therefore prevented the complete reconstruction of the 3D models. The camera aperture was set in aperture priority mode at F8. Unfortunately, the distance could not be kept constant, so the autofocus was set to prevent some objects from being out of focus. In this photogrammetric survey, a calibrated bar of approximately 8 cm was placed at the foot of the two models (Figure 1), at a distance of approximately 50 cm from the artefacts. The calibrated bar was used to constrain the scale of the models. This arrangement was due to safety reasons, so as to not compromise the integrity of the anatomical machines in any way, but it predictably resulted in a sub-optimal scaling of the two models, which consequently affected the dimensions of the organs and bones of the skeleton (distant from the feet).

Figure 1. Calibrated scale bar placed at the foot of the female anatomical machine.

Figure 2. Acquisition geometry of the female Anatomical Machine.

The resulting medium GSD was of 0.06 mm and the geometry of the photographic framing was slightly convergent, which is typical of close-range surveys (Figure 2). Moreover, the overlap among the images ensured a multiplicity of tie-points (i.e., the number of images in which the same point is captured) greater than 9 on both the bodies.
A second photogrammetric survey was carried out on the 1st February 2022, using the same camera of the first acquisition equipped instead with a 20 mm lens, holding the focal length constant. During the post-processing operations, the scale constraint was set using a 3D model acquired by the KSCAN-MAGIC handheld laser scanner.
For both the surveys, the images were oriented with Agisoft Metashape ver. 2.0 software using approximate internal orientation parameters and subsequently refined with the auto-calibration procedure.

3.2 Laser-Scanning acquisition

On the 18th January 2022, a different methodology was employed to obtain the two 3D models, based on the use of the handheld laser scanner KSCAN-MAGIC manufactured by the Scantech company. This type of instrument produces laser patterns made up of dots or lines on the surface of the object; moreover, a camera sensor is placed at a fixed distance from the laser emitter to capture the position of the laser features. This kind of instrument is generally employed for industrial applications, where high-precision measurements are needed. The obtained point clouds do not contain information about the colours, since the KSCAN-MAGIC is not equipped with an RGB camera.

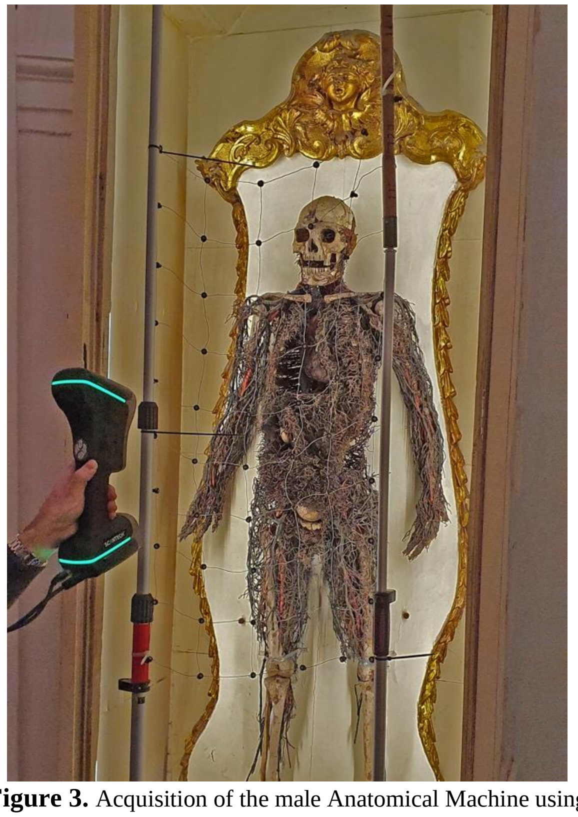

Figure 3. Acquisition of the male Anatomical Machine using KSCAN-MAGIC and the Target-Net.

To facilitate the alignment of several scans, it is generally necessary to use targets preferably positioned on the object to be scanned or, if this is not possible, in the scene. In this case study, the aforementioned motivations prevented the direct contact with the Anatomical Machines, and a distance of at least 0.5 meters had to be kept. To overcome this drawback, a Target-Net (Figure 3) was used: it consists of a semi-rigid network of markers interposed between the scanner and the artifacts. Since the stand-off distance of the KSCAN is 30 cm, the acquisition was performed from a distance of at least 80 cm.
The KSCAN-MAGIC can employ two different laser wave lengths: blue and infrared light. In this work the infrared light was used and the spatial resolution was set at 1 mm. Therefore, due to the large acquisition distance, some details on the final 3D model are missing.
The final 3D points cloud for the female and male Machines are composed by 6.6 and 5.3 million of points respectively.

3.3 Scaling setup

The point clouds provided by the laser-scanner acquisition were processed to remove the target network along with some noise and spikes. The result is a smooth 3D point cloud with a resolution which was not sufficient to represent all the details of the Anatomical Machines (Figure 4-6). The 3D coordinates of five natural targets easily identifiable on the images (Figure 5), were extracted from the clouds.

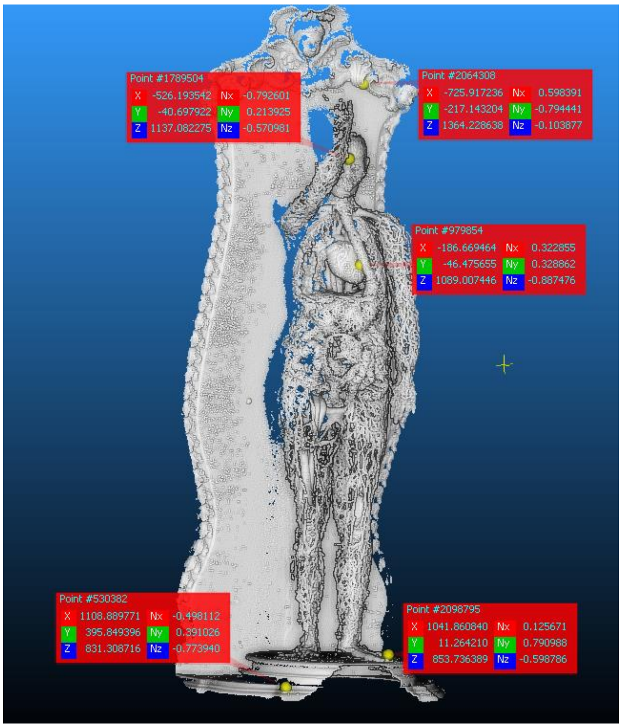

Figure 4. 3D Laser Scanner model of the female machine with the five points used as GCPs.

Such targets were used as GCPs (Ground Control Points) for scaling the photogrammetric point cloud and to further align it toe the Laser Scanner coordinate system.
The GCPs coordinates were used as constrain during the bundle adjustment of the photogrammetric processing. They played a key role in improving the accuracy and reliability of the photogrammetric model, since these points are considered as ground truth constrain; in fact, the bundle adjustment optimizes both the camera parameters (internal and external) and 3D coordinates of the points of the model. The final accuracy can be estimated by comparing the 3D coordinates of the GCPs with their initial values the final results provide a mean error on the GCPs of 2.1 mm for the female machine and 1.3 mm for male machine.

Figure 5. An example of GCP picked up on an image: it can be noted that, in this case, the point is on the right ventricle of the woman’s heart; the high complexity of the reconstructed circulatory system near the heart can also be seen.

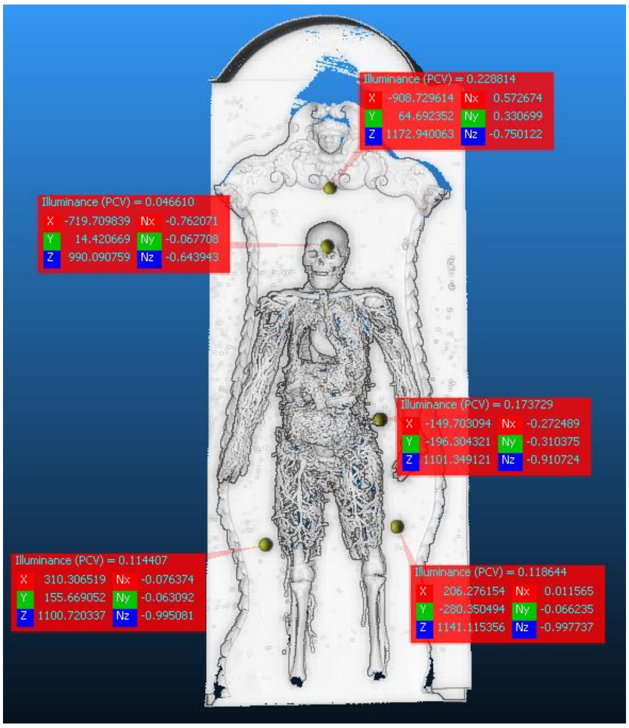

Figure 6. 3D Laser Scanner model of the male machine with the five points used as GCPs.

4. RESULTS

4.1 Photogrammetric surveys

The first survey produced 167 frames for the male Anatomical Machine: its model was obtained trying to maintain a very wide average overlap among the images. It should be noted again that the average multiplicity is greater than 9, with a typical geometry for close-range surveys with slightly convergent setups. It was not possible to push too much on the convergence due to the presence of the wood theca.
The female Anatomical Machine model derived from the processing of 170 images: even in this case, we tried to assure a very wide average overlap, with an average multiplicity greater than 9. Both the results are noisy: this depends on the choice of setting the automatic focus to avoid parts of the images from being out of focus. In fact, the used lens allows to obtain a very low GSD on the model even from a moderate distance, with the consequent improvement of the noise.

Table 1. Results obtained, for the male and female Anatomic Machine, in the first photogrammetric survey.

Parameter	Male	Female
N° of images	167	170
Accuracy	Medium	Medium
Mean GSD	0.06 mm	0.06 mm
RMS reprojection error	1.67 pixel	1.93 pixel
N° of raw points	42.871.411	47.328.489

However, despite the same acquisition conditions, the female survey geometry resulted to be better than the one of the male: this is due to the fact that the former is positioned further forward from the background. This condition made it possible to obtain a more complete 3D model since it was possible to photograph some side parts of the artefact. From Figure 7 it is possible to understand the morphological complexity of the model and, limited to the anterior part, its completeness. The final model noise is further proved by the various outliers in the scene that deviate from the model; however, these gross errors can be easily identified and removed, making the 3D model result acceptable.

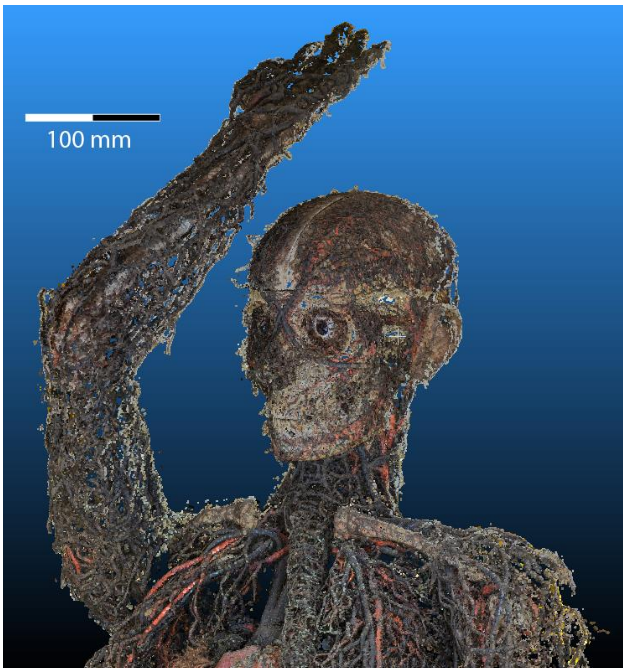

Figure 7. 3D reconstruction of the upper part of the female anatomical machine, nearly later view.

The second photogrammetric survey was realized to improve the previous results, using a shorter focal length which has been mechanically kept constant. This led of course to an increase of the GSD but at the same time the final 3D model resulted much less noisy (Table 2).

Parameter	Male	Female
N° of images	146	170
Accuracy	High	High
Mean GSD	0.16 mm	0.16 mm
RMS reprojection error	1.06 pixel	1.46 pixel
N° of raw points	60.804.144	120.251.009

Table 2. Results obtained, for the male and female Anatomic Machine, in the second photogrammetric survey.

4.2 Anthropological and palaeopathological analysis

With the aim of determining the sex of the two Machines models, the distances between the landmarks were measured in the second photogrammetric survey. Moreover, the distance between intercondylar eminence and the medial malleolus of the left tibia (see Figure 8) was determined in the male model to measure anthropometric features.

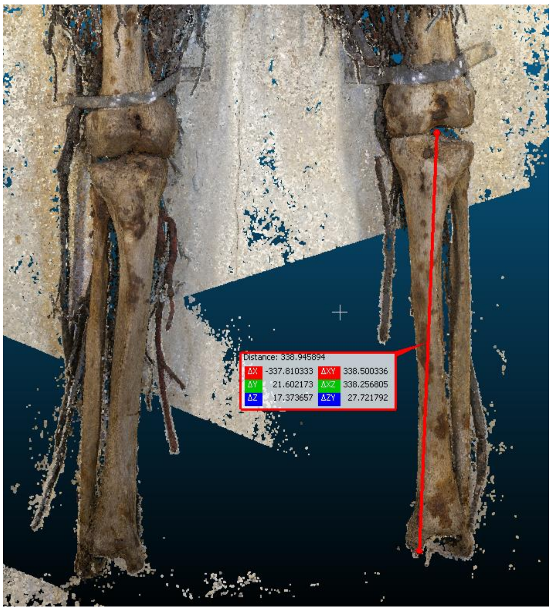

Figure 8. The measured distance between intercondylar eminence and the medial malleolus of the left tibia on the 3D model of the male anatomic machine.

Unfortunately, their position inside the wood exhibitors and the consequent survey limitations did not allow for the examination of the posterior portion of the Machines. Therefore, it was impossible to clearly determine whether the female model had pulmonary atresia or not.

5. CONCLUSION AND FUTURE WORKS

This article presents the results of a series of survey conducted on the Sansevero Chapel Anatomical Machines (Naples). Commissioned by Raimondo di Sangro and crafted by Giuseppe Salerno in the 18th century, these complex artifacts present unique features and anatomical evidence which raised challenges but also provided a valuable foundation for the related 3D modelling techniques.
The meticulous examination of the historical records and the scientific analyses of the Anatomical Machines allowed to disprove the myth of their creation through injection and revealed instead the complex construction involving metal wire, wax and silk fibres. In this context, the geomatic surveys gave a fundamental contribution to the understanding of their anatomical and palaeopathological aspects, despite the encountered operational difficulties. In fact, their fragility and their position inside the glass exhibitors required for a non-invasive approach which could at the same time assure the reliability and accuracy of the resulting 3D models, especially in relation to their correct scaling.
Despite these challenges and some minor inaccuracies, the 3D models achieved results remain acceptable, demonstrating the potential of this photogrammetric and laser scanning combined approach in studying ancient human remains and other artifacts.
However, challenges remain, especially in examining obscured portions of the models. Future work in this field should focus on refining these survey techniques, also leveraging advancements in NERFs (Neural Radiance Fields) architectures to enhance the accuracy and completeness of 3D models which are hardly accessible and manoeuvrable. NERFs have in fact the ability to reconstruct complex scenes from sparse data, thus holding promise for overcoming challenges related to inaccessible regions to improve the overall model fidelity. Additionally, further interdisciplinary collaboration will foster ongoing progress towards continued advancements in the field of cultural heritage preservation and anatomical, archaeological, and paleo-archaeological research.

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