Mixing Methods – The Use of 3D Techniques at the Ancient Villa of Capo di Sorrento

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Accompanying excavation activities in the area of the Roman luxury villa of Capo di Sorrento, 3D models of the landscape and relevant features have been created using mostly Structure-from-Motion (SfM) since 2015. With this method, it was possible to create a digital surface model of the excavation site combining terrestrial, aerial, and underwater photography. From this 3D model and other, more detailed sub-models of specific objects or areas, various new data were created that greatly enhance excavation documentation and the assessment of features. While some of these data, such as orthophotos generated from SfM models, are now standard practice on excavations, other products require more effort. The research project on the villa of Capo di Sorrento went beyond the results that were obtained from 3D models, and are usually presented as 2D pictures, to expand on the 3D data collected in the field in later work. In particular, the reconstruction of a grotto triclinium based on SfM models is combined with manual and tacheometric documentation to yield far-reaching insights into the architecture, furnishings, and orientation of the rooms on the north side of the pars maritima. Renderings of 3D data are used to simulate the views from certain points. This reconstruction is thus based on both the archaeological features and the specifications of the surface models and as such combines different methods of 3D processing, and fuses digital data with analog research results. Over the course of several excavation campaigns, a corpus of 3D products has grown within the research project. The respective methods of data acquisition, processing and analysis are primarily due to the landscape conditions of the study area. The detailed representation of the rocky subsoil – i.e. the heavily manipulated limestone plateau at the northern end of the cape – above and below water played a central role.

Keywords:
3D Data, SfM, Reconstruction, Field Documentation, Visualization, Building Archaeology.

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1. INTRODUCTION

Following only sporadic and disjointed exploration attempts, the Roman luxury villa of Capo di Sorrento has been under archaeological and architectural investigation since 2014 [Filser et al. 2017, pp. 71-73].

Only a few of the irregularly preserved seaside villas on the Sorrento Peninsula remain accessible today, as most were overbuilt in modern times or have fallen victim to the forces of nature to such an extent that they are weathered beyond recognition. The comparatively well-preserved villa at the Cape of Sorrento (Fig. 1) is considered exemplary among these complexes, which were built and maintained from the 1st century B.C. until the eruption of Mount Vesuvius in 79 A.D. [Mingazzini and Pfister 1946, pp. 121-132; Bergmann 1991, pp. 49, 51-52; Lafon 2001, p. 424; Filser et al. 2021, p.131].

Figure 1. Aerial view of the Capo di Sorrento and the remains of the villa [W. Filser].

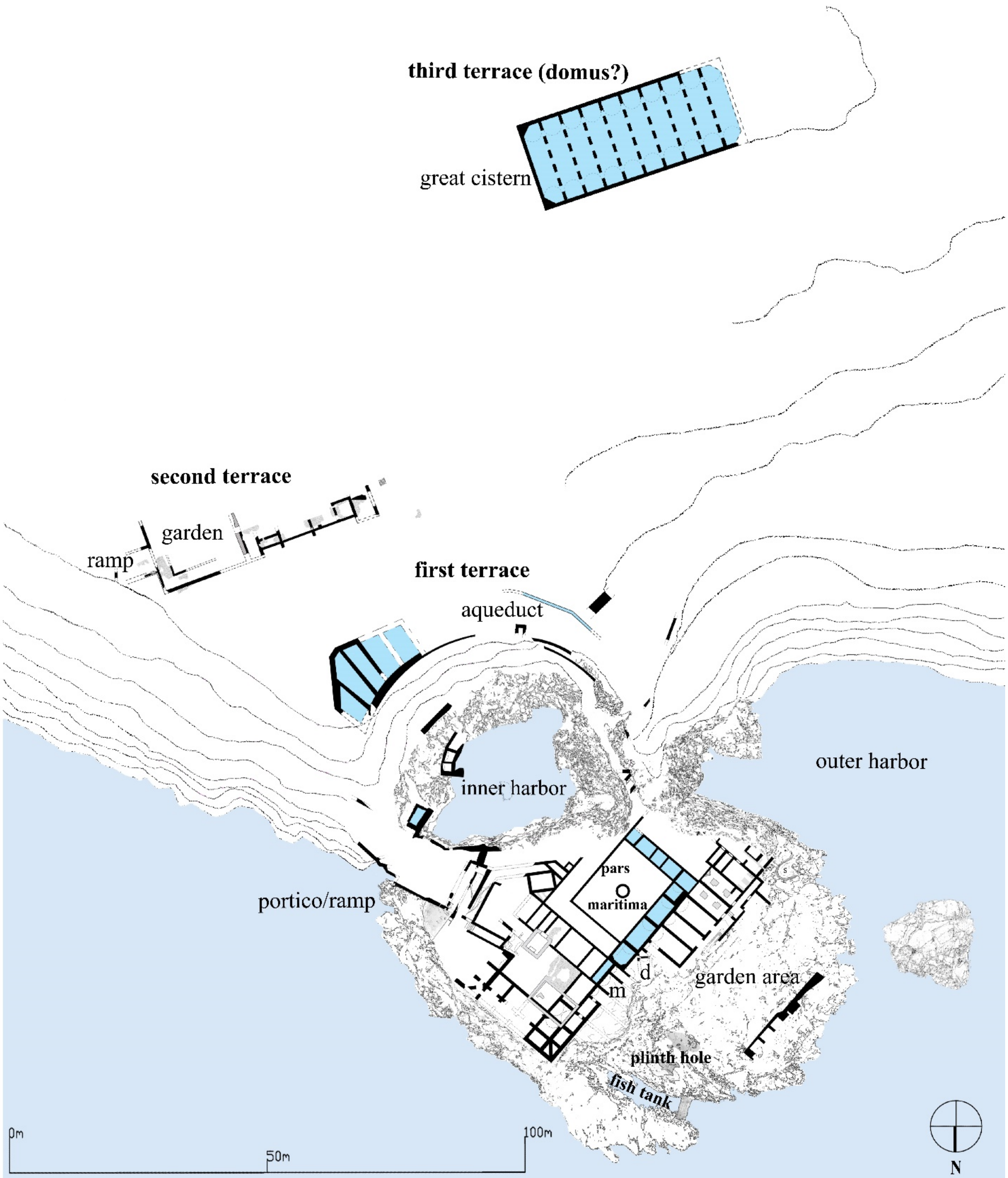


Figure 2. Map of the excavation area [W. Filser, C. Klose, W. Kennedy, S. Götz].

The appearance of these terraced buildings was calculated to the smallest detail, as well as a variety of individual perspectives that connected different rooms of the villa with landmarks in the Gulf of Naples. For this reason, slopes and projecting capes were preferably chosen as sites. Elaborate substructures and artificial terracing as well as the development of suitable bays into small harbor facilities were part of the building program. In addition to extensive landscaping, the villas also incorporated opulent and highly individual architectural-artistic and economic-infrastructural features such as fish breeding ponds or widely ramified water networks.

The *pars maritima* of the villa of the Cape of Sorrento is located on a limestone plateau directly by the water, while the main buildings and the part of the complex that was presumably also used for agricultural purposes were spread across several terraces above it (Fig. 1-2). The two areas are separated by an approximately circular basin which, together with the rectangular bay to the west of the *pars maritima*, functioned as a harbor.

The owner of the extensive complex remains unknown. The building suffered multiple destructions caused by earthquakes and remodeling after its initial construction during Late Republican times before it was finally destroyed and abandoned (at least with regard to its use as a marine villa) in the second half of the 1st century A.D. – probably shortly before or during the eruption of Vesuvius in 79 A.D. [on chronology Klose 2016, pp.66-68; Filser et al. 2017, pp. 90-94; Filser et al. 2021, pp. 143-144].

The heterogeneity of the topography and the archaeological features form precisely the conditions that allow documentation and analysis to be carried out effectively using 3D techniques. In this context, the overall picture is formed by using different acquisition techniques as well as by the use and combination of point-cloud based 3D data (SfM, laser scan) and also not-point-cloud based (but NURBS-based) 3D modelling reconstructive data and data products dependent on them.

Overall, the use of several digital 3D techniques in this project forms a suitable starting-point [Attenni et al. 2020, p. 266] for an in-depth analysis of the archaeological and architectural features of the Roman villa.

2. METHODS

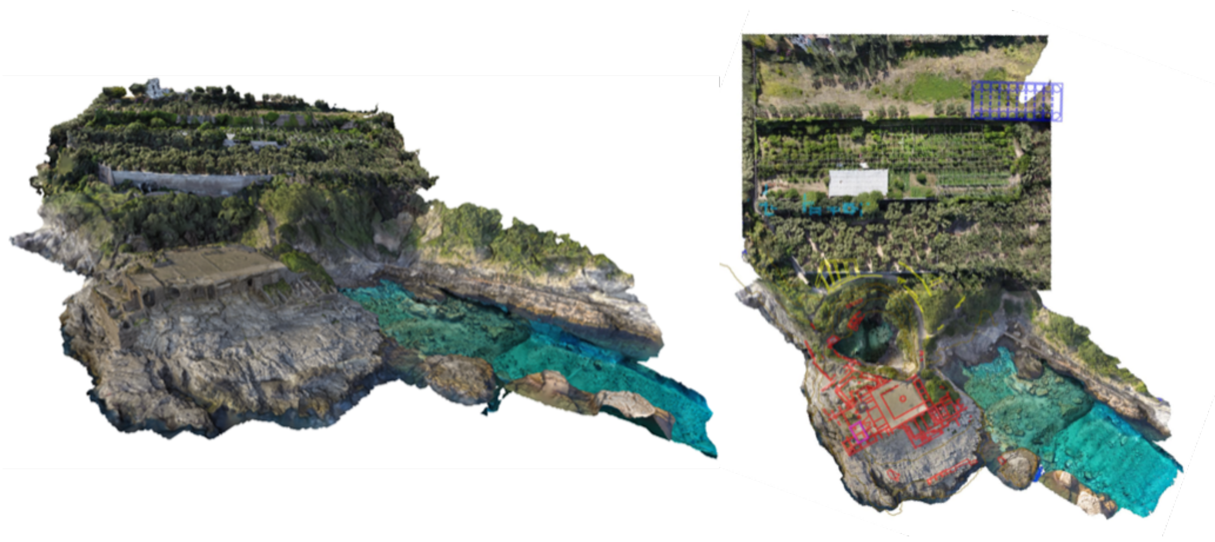
In addition to conventional excavation documentation, 3D data of the investigation area has been collected since the beginning of the project. However, problems with on-site transportation and the provision of a stable power source proved the handling of a laser scanner to be impractical. Apart from logistical difficulties, laser scans would not have been able to optimally survey many areas of the site.

In contrast, the use of Structure-from-Motion (SfM) proved advantageous in several ways. First, large areas could be covered with photos from an UAV (DJI Phantom 4 and DJI Mini 2) and second, smaller more difficult-to-access areas as well as excavation sections could be documented with an SLR camera (Nikon D 800) in high quality 3D from the ground. The images were processed using the latest versions of Agisoft Photoscan/Metashape. In this project, SfM is used to enhance the manual documentation of small finds and to model the complete landscape of the cape, thus making it conducive for geological-geomorphological questions (e.g., concerning artificial and natural changes that have affected the building site since Roman times). Furthermore, the two harbors of the villa could be included in the investigation and the resulting photos and films could also be calculated into a 3D model. Thus, a digital surface model of the remains and the building ground of the ancient villa has been produced on the basis of data collected on land, under water and from the air (Fig. 3).

Going beyond extensive discussions on the use of 3D data and specifically SfM as a primary documentation method (see e.g., [Anderson 2021; Sapirstein 2021]), this paper presents the digital products and tools that can be created based on SfM and thus aims to demonstrate how these can be an important addition to the standard documentation methods currently in use. These products depict the crucial added value of recording archaeological structures in 3D and can be very diverse (see also Di Giuseppantonio Di Franco et al. 2018).

In addition to the clear visualization of the villa's structures, analyses and surveys of the site can be carried out using the 3D data only and thus without being physically present on the cape. In a further step, it was possible to reconstruct entire rooms or even groups of rooms based on SfM models, which provided further insights into the architecture and furnishings as well as into questions of visual axes and alignments of the components of the villa.

The SfM models of the investigation area, which have already been created from a mixture of different photographic techniques, thus form a core of data from which an array of further data products can be created. The resulting virtual reconstruction of the *basis villae* (its facade, the surrounding flight of rooms, and its upper floor) shows how valuable an accompanying documentation in 3D can be from the beginning, in some cases with the aid of comparisons to other sites (for a similar approach see Micoli et al. 2017). The interaction of different 3D techniques and the resulting new products (in 2D or 3D) are described below.



a b

Figure 3. a) 3D model of the area of the roman villa of Capo di Sorrento including the seafloor of the two harbors [B. Fritsch, M. Reinfeld, W. Filser], b) Orthophoto created from the 3D model including the excavation plan [W. Filser, W. Kennedy, B. Fritsch]

3. CHALLENGES

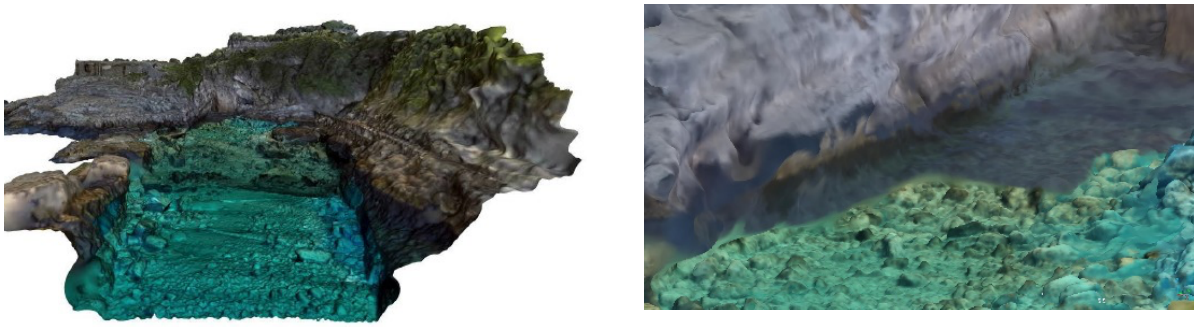
Over the course of several campaigns, it was possible to repeatedly expand the 3D data on the study area, using several methods and approaches and finally, among other things, combining them into a complete base model.

In the first campaign, which intended to create 3D data, a laser scanner (Leica Scan Station 2) was used. However, good results could only be obtained for the front of the *pars maritima* in the central area of the site. Later, however, this point cloud was used exclusively as a reliable basis regarding size and scaling of future SfM models (for a similar approach see Micoli et al. 2013, p. 4). Yet this method was not suitable for an overall survey of the excavation area. Not only were transportation and power supply of the laser scanner out of the available budget in the long-term, but also it was impossible to scan the required landscape conditions and surface structures of the ruin within the given time frame.

The terracing and the layout of the villa, open to water on three sides, could be much better captured with Structure-from-Motion gained by aerial and terrestrial photography. With the help of an UAV (DJI Phantom 4), a model of the lower area (*pars maritima*) was created, starting in 2016. In the areas where the UAV could not provide sufficient footage (e.g., in the interiors, narrow paths, or elements reaching over the water), photos were taken with an SLR camera from land or from the water using a canoe. Likewise, areas of particular interest as well as the excavation trenches were recorded in small scale and detail in SfM. All individual models were scaled by using target points that were laid out and measured by distance within the field of the field of view of the camera. Eventually the single models were integrated into the overall model using the open-source software Meshlab [Cignoni et al. 2008] for cleaning and orientation and CloudCompare for aligning the models in a two-step procedure (raw manual alignment following automatic fine alignment).

Since the villa also had a harbor consisting of two separate basins, this was understood as an essential element of the site and was investigated in the form of an intensive survey. Both harbor basins were documented in several campaigns with sufficient image material taken by divers (using a Canon EOS 550 D with Dome Port DP180 A20 and a GoPro 5 with a standard underwater case), which allowed the creation of 3D models of the seabed in both areas.

In total, 24,500 individual frames were extracted from approximately seven hours of video footage of underwater recordings using the free software ImageMagick [ImageMagick], which in turn were processed using the SharpEdge filter [Weinhaus 2018]. Due to the frequently changing light and visibility conditions that influence underwater images, it was not possible to compute all images in a single, coherent model. For the larger outer harbor, 30 separate sub-models were created, which were roughly oriented and scaled using a clear raster image in Meshlab, and finally merged in CloudCompare using the 'Align' functionalities (Fig. 4a).



a b

Figure 4. Underwater SfM recording: a) Outer harbor [B. Fritsch]; b) Intersection between the underwater model in front and the terrestrial model in a flat-water area [B. Fritsch].

Compared to the use of SfM on land, underwater photography presents additional challenges when generating usable photos: stormy weather that churns up the water and obstructs visibility, rapidly changing light conditions, and also large schools of fish that can completely obscure the desired objects for short periods of time [Reinfeld et al. 2020]. However, even after successfully generating a 3D model, the difficulty of connecting the underwater model to the terrestrial model remains. The side walls of the harbor basin were photographed and subsequently generated in 3D as well. Still, as the sea level varied due to being photographed on different days or necessarily different dives an overlap with the land model could not always be guaranteed.

Also, in the shore zone, both types of recordings (on land/under water) reach their natural limits: While the onshore imagery can easily capture the underwater structures in the shallow water zone, the mesh still maps the water surface. Conversely, in those shore areas which are only a few centimeters deep, it is no longer possible to take underwater pictures of sufficient quality. At this point, the model consequently reveals a step from the water surface to the seafloor that cannot be closed with the capabilities of SfM (Fig. 4b).

Similar difficulties also arise with land-based SfM. This is especially the case for stratigraphic excavations of larger but disjointed structures that occur over several years but can only be documented at specific times. Although vegetation can be removed in small areas during the excavation campaign to allow a clear, ideal view of the features for SfM recording, the vegetation is constantly changing, making it difficult to incorporate individual 3D models or update 3D models in the following year. Apart from the basic obstacles posed by vegetation, which also arise with other high-end methods such as LiDAR scans [Doneus et al. 2022], a special feature of the Sorrento cape is that the two lower ancient terraces of the villa are now used as a communal orchard and an olive grove, while the top terrace is privately owned and currently relatively unvegetated. A large-scale reduction of vegetation during the excavation campaign is therefore simply not possible. Thus, in some areas, 3D modeling of the soil or the modern ground level must be omitted. However, this is negligible when considering the entire site, since decisive measurement points could be recorded in the individual excavation sections between the trees.

An exception to the use of SfM was made in the recording of the large cistern in the building ground of the third terrace. This cistern consists of ten identical chambers (with the exception of the reinforced corners in the first and tenth chambers), most of which are now filled with mud. In addition, since there are no special structures, contrasts or decorations and very poor lighting conditions, it is very time-consuming to take photos of sufficient quality (including artificial lights) and the processing is bearing a higher risk of misalignment. In this case, a fortunately available laser scanner (BLK 360) was used (Fig. 5), since the external circumstances represent one of the very rare cases in which this device offers more advantages than SfM.

Figure 5. Scan of the great cistern: a) Point cloud of the laser scanner [W. Filser, B. Fritsch]; b) View into a single chamber [W. Filser]; c) plan of the cistern [P. Mingazzini].

The surface model is thus subject to constant change and is composed of different forms of data. This necessary diversity constantly provides fresh opportunities to create new and diverse data products and expand our knowledge.

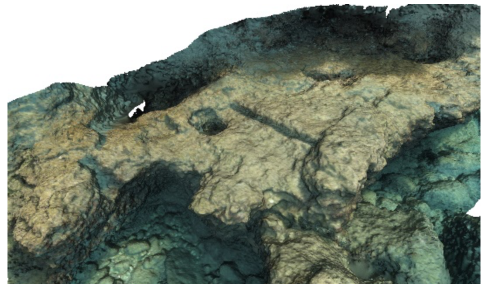
4. DATA PRODUCTS

The results that can be determined with the help of 3D data are extremely diverse, and similar to the flexibility of SfM, offer a wide range of small and large insights.

For instance, the documentation of the harbor basins and subsequent processing of their side walls made it possible to prove that the basins were artificially altered and lavishly decorated in a representative manner. On the seabed in front of the three islets, fallen architectural parts and remains of small and medium-sized (marble) columns (Fig. 6a) could be identified during the 2015-2021 surveys [Reinfeld et al. 2020, Filser et al. 2021, pp.139-140]. By determining their positions, the locations where the heavier debris fell from the villa into the sea can be established in the 3D model.

Using this method, architectural fragments as well as the remains of a presumed jetty could be detected in the outer harbor basin (Fig. 6b) [Reinfeld et al. 2020; Filser et al. 2021, pp. 140-141]. From the jetty, only the worked limestone rock can be seen, on which a caementitium construction was erected as a foundation. Such constructions are known from comparable sites in Italy [Felici 1993; Felici 2006]. In the next step, a complete reconstruction of the installation can be derived from the overall model and well represented in its original context.

a



b

Figure 6. Underwater 3D-data: a) architectural fragments including remnants of a small columns beneath the bigger block [M. Reinfeld, B. Fritsch]; b) Worked limestone rock on which a caementitium construction was erected as the foundation of the jetty [M. Reinfeld, B. Fritsch].

The 3D model is also extremely helpful in providing an overview of the entire terraced area, which one cannot see from individual positions in the field. Over the years, it has been possible to excavate the various occupation layers of the individual levels. This way, the original terracing, which was already carried out in ancient times, could be proven and visualized in the 3D model in an easily comprehensible way. For this purpose, corresponding fitting planes were created in the free software GOM-Inspect [GOM Metrology] at the level of the proven soil features, so that the distances between the planes can be measured and the ancient and the present running horizon can be precisely visualized (Fig. 7 and 8).

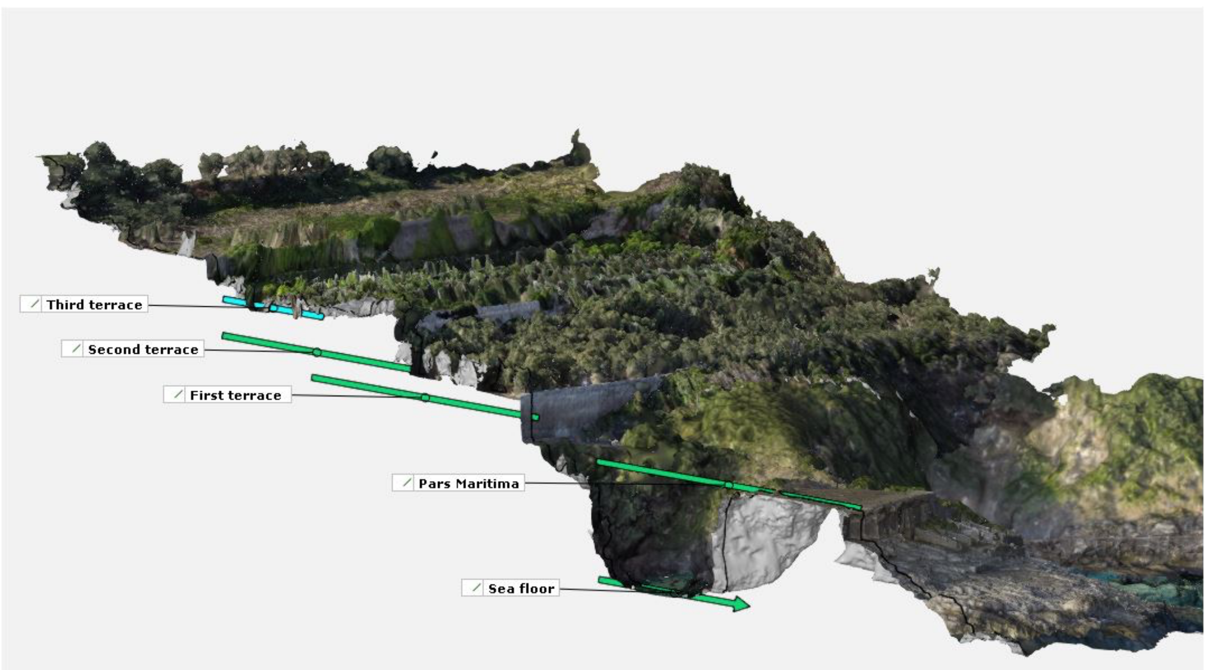


Figure 7. Fitting-layers of the different horizons of the villa. The horizon of the third terrace is not completely secure yet [B. Fritsch].

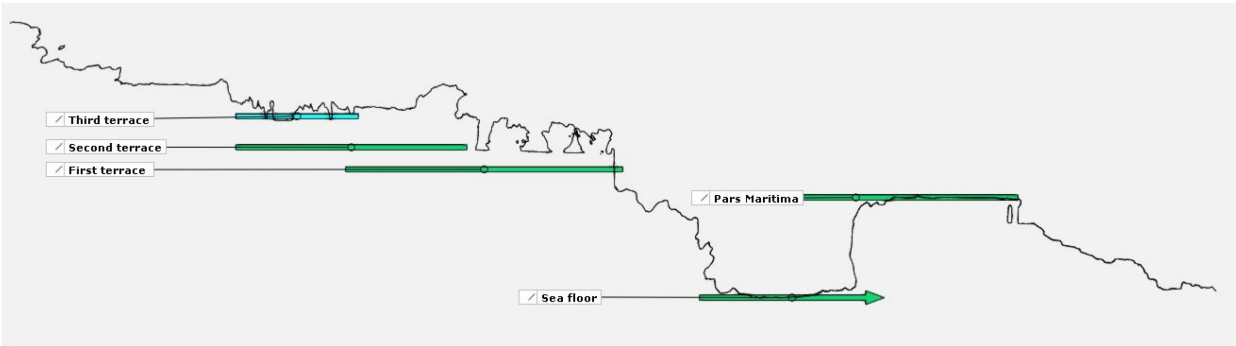
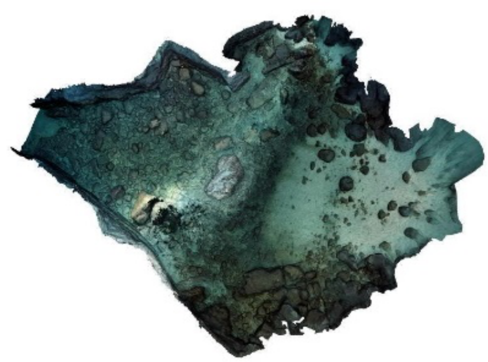


Figure 8. Fitting-layers of the different horizons compared to a contour slice of the actual situation [B. Fritsch].

3D models can also provide an important contribution to the investigation of smaller features simply through their visualization. For example, the 'footprints' of a monumental bronze statue were discovered at the edge of the inner harbor. Due to the barely accessible location, namely the changing light conditions and the wear and weathering of the rocks, these footprints are not always easy to recognize. The 3D model of this sub-area removes any environmental disturbances and allows a very precise view of all its features, since the lighting conditions and contrasts in the virtual space can also be controlled to a certain degree (Fig. 9a).

This method is also used in the analysis of inscriptions in order to reproduce them in a completed form [e.g. Mara 2016, most recently Helmke et al. 2022]. Similarly, but on a much larger scale, it is used for the entire facade of the *pars maritima*, to produce a model that is not affected by any shadows which would be unavoidable in conventional aerial photographs. This is also particularly helpful for the entire 3D underwater documentation of the ancient harbors, as the refractive light and the distortions caused by water and waves can be digitally eliminated from the 3D model to provide a clearer and, for the first time, more coherent large-scale view of the now sunken structures on the seafloor (Fig. 9b).

a



b

Figure 9. a) Traces of a statue on the north side of the inner harbor on a small plateau [W. Filser, B. Fritsch]; b) Seafloor of the outer harbor with different light conditions [M. Reinfeld, B. Fritsch].

Orthophotos in the form of basemaps, elevations and wall views belong to the standard products resulting from the work with SfM, also in this project. They were combined with the tacheometrically surveyed overall plan (Fig. 2) for integration into a Geographic information system (GIS) project which allows for precise mapping and scaling of both the entire site and single details (Fig. 10).

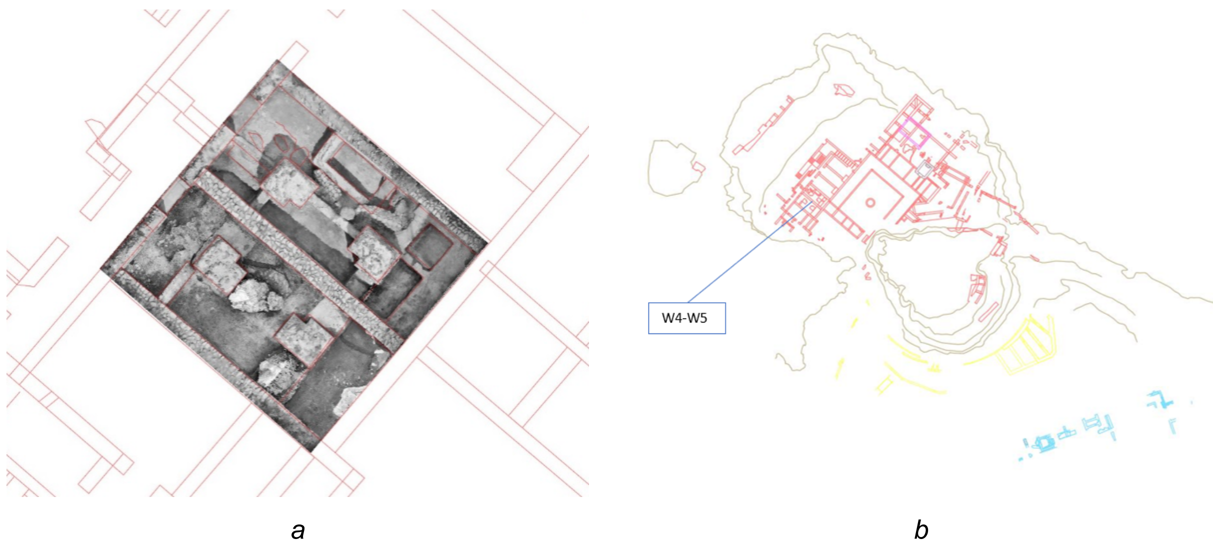


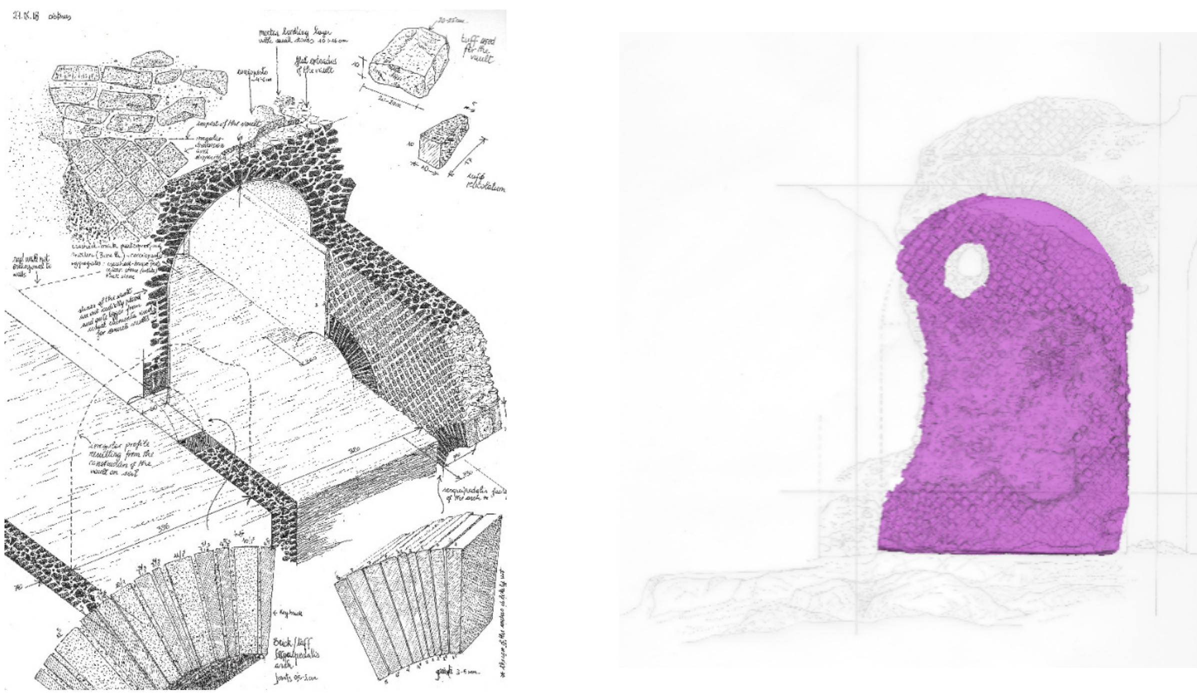
Figure 10. a) Orthophoto of room ,W4-W5' embedded into the plan in QGIS [W. Filser, B. Fritsch, C. Klose]; b) Complete plan of the villa [W. Filser, W. Kennedy].

But the process of analysis of the structures needs integration with more traditional tools of documentation. For this reason, an important component of the research concerns also the way digital tools are integrated with the traditional survey techniques. In order to achieve full understanding of the remains and developing the hypothetical reconstructions, the scrutiny of structures does not only involve the record of what is visible, but also the interpretation of the traces. Man-made artifacts are the result of processes in which materials are selected, transformed and assembled. The "archaeology of the building" needs the Bauforscher (the building researcher) to interact with the building in an attempt to interpret the processes that determined its current condition. It is thus a matter of going beyond the "skin" of the building, and understanding how the whole fabric was designed and built to achieve the architectural program, to what level the construction process was faithful to the design and best quality principles, and which events altered the building after having been achieved. The methodology aims at interpreting through the build evidence, all the construction history of the building, including its building phases, damages and interventions occurred from the moment it was built to the moment we analyze it, and framing this into the building culture that produced every single phase of its life [Schuller 2002, Brogiolo and Cagnana 2017].

Hand drawings can be developed from digital tools. Typically, an orthography can be used to start the on-site analysis. It is then a matter of sitting down and spending time to observe the parts of the building under analysis. Drawing by hand in front of a wall is an exercise which involves a series of queries that the observer can answer by getting closer to the structure, looking at the composition and stratigraphy of materials, and penetrating mentally into the logical process of the mason who assembled the masonry. Observations are then transferred into the drawing.

Drawing a line is not as trivial as it may seem. It is difficult when using digital tools and is equally difficult in hand drawing. The aim is to express the “identity” of the object, by offering an objective and communicative graphic representation. However, in hand drawing the mental link between the object and the person, makes this selection process easier and more incisive.

Frequently this kind of drawings can be developed also through axonometries, as can be seen in the drawing of a cistern (Fig. 11a). This drawing summarizes the understanding of the object, and exemplifies how the information that is gathered on-site supports the whole sets of hypotheses necessary for the interpretation of the object.



a *b*

Figure 11. a) Hand drawing of the small cistern [P. Vitti]; b) Overlay of SfM model and hand drawing [P. Vitti, S. Götz, B. Fritsch].

Thus, digital and manual tools are equally necessary, and need to interact to achieve a meaningful result (see also Fig. 11b).

Such highlighting of detailed information about individual features, which supplements the general field documentation, demonstrates the added value of digital methods in everyday excavation work (it remains to be seen what grade of automatization will be reached in the future through ongoing software development; see for example the Masonry Segmentation Tool for CloudCompare by [Valero and Bosché 2020]). Apart from this, the surface model of the villa site (Fig. 3) can also be useful as a laboratory and starting point for exploring larger architectural structures. It can be used to apply, test, and develop hypotheses for the reconstruction of individual spatial units which form the first phase of the overall reconstruction of the ancient appearance of the villa and its natural surroundings.

5. RECONSTRUCTION

The examples above show that SfM models are a versatile addition to archaeological and architectural investigations. The possibilities of three-dimensional documentation and, beyond that, of working in virtual space are far from being exhausted and offer new ways of opening up features. One option is the virtual three-dimensional reconstruction of ruins. The SfM models help to reconstruct lost structures in three-dimensional virtual space.

With a few exceptions [see for example Limoncelli 2019], the method, in which photogrammetric 3D models are directly integrated into the process for virtual reconstruction, has not yet established itself in high quantity and quality in archaeological research. This paper aims to demonstrate the potential of this method as a complementary, versatile tool for archaeological research.

As an excellent example of this procedure, the virtual reconstruction of a grotto triclinium inserted into the *basis villae* on the north facade of the *pars maritima* is presented here. In the course of the investigations, it could be proven that the room *"m"* (see Fig. 2) had a nymphaeum with a water staircase and offered a *prospectus* to the landmarks Puteoli and Misenum on the other side of the Gulf of Naples through a wall opening to the north. This room was clearly a small, luxurious retreat within the extensive villa complex (a final publication on the villa at the Cape of Sorrento will present these new results in more detail). The identification and reconstruction of the grotto triclinium are based on a variety of different heuristic tools and sources:

I. Observations from the archaeological record.
II. Plans, drawings, photographs and descriptions of current research.
III. 3D models from SfM.
IV. Plans, drawings, photographs and descriptions of the results from older publications.
V. Comparable preserved and appropriately well-published Roman buildings.
VI. Representations of villa complexes in Roman wall paintings and reliefs.
VII. Descriptions of villa complexes in historical sources.
VIII. Historical texts and images (travelogues, photographs, engravings, etc.).

This guideline for the reconstruction of ancient architecture was also the basis for the virtual reconstruction of the grotto triclinium, wherein the first three points are crucial. In the following passages, the focus will be on the importance of the SfM model of the study area for the virtual reconstruction of the grotto triclinium.

Using 1623 photographs taken with a Sony Alpha 7, a high-resolution and detailed SfM model was created of the area around room *"m"* of the north facade of the *pars maritima*. This digital documentation of the ruins of the grotto triclinium, made in 2019, was the basis for the virtual reconstruction. After its generation, the SfM model was georeferenced in the photogrammetry software and scaled according to the metric system in its real dimensions in virtual space (Fig. 12).

a

b

Figure 12. Detailed SfM model of the grotto triclinium (room with opening in the back wall) in the north facade of the villa at the Cape of Sorrento. a) Oblique view [S. Götz]; b) Frontal View [S. Götz].

In recent years, photogrammetric models have reached a high level of accuracy that is equivalent to laser scanning in its usefulness for archaeology [El-Hakim et al. 2008; Doneus et al. 2011; Lieberwirth et al. 2014] and for subsequent reconstruction [Sapirstein 2016, p. 143-144].

The scaled 3D model of the grotto triclinium was imported into the 3D graphics software Cinema 4D in OBJ and also FBX format [Maxon Computer GmbH. *Cinema 4D*]. Programs of this type were once designed for animation in film, TV, and gaming, but also offer new possibilities for archaeology. In this case, the SfM model imported into Cinema 4D's virtual space acts, among other things, as a three-dimensional plan that forms the internal framework for the reconstruction. The digitized remains of the grotto triclinium, such as the floor level, lengths, widths, and heights of the walls, now served as a template for the architecture that no longer exists. The SfM model clearly shows the different room heights of the preserved vaults; it is here that the SfM model serves particularly well as a reference for reconstructing the rising architecture to scale in terms of its height and extent (Fig. 13). Moreover, the SfM method also documents the architecture in color and can be recorded as a texture in three-dimensional space, so that color remnants also contribute to the modeling and can be considered later in the reconstruction.

In this way, it was possible to create a virtual model of the grotto triclinium directly from the digital results of the SfM model. The structures modeled on a polygonal basis are attached and adjusted to the digitized remains of the grotto triclinium. A connection takes place between the SfM model and the reconstructed elements, with the new modeling filling in the gaps of the lost architectural structures and virtually reanimating the ruins.

This is particularly evident in Fig. 13. The figure shows a process during the reconstruction work in the three-dimensional medium. The southern longitudinal wall of the grotto triclinium was reconstructed from its remains in the soil and limestone rock up to the remains of the vault's impost zone. Here one can clearly see how closely the reconstruction follows the SfM model. The surviving stucco and plaster from the late 1st century B.C. of the room overlaps the reconstructed wall, which is based only on the core wall and its sheathing of *opus reticulatum*. The reconstructed wall and documented vault smoothly merge into each other. The dimensions and execution of the reconstruction were precisely matched to the digitized context.

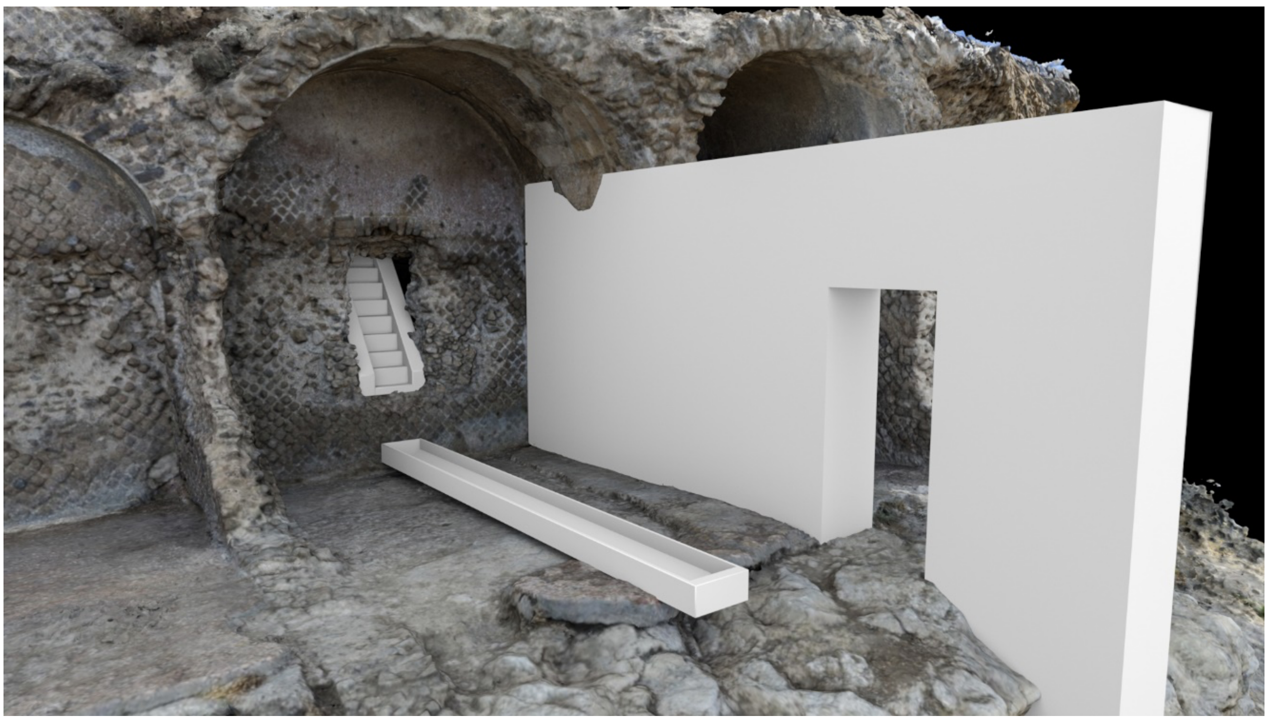


Figure 13. Reconstruction process. Inserted wall, passage, cascade and water channel [S. Götz].

Furthermore, Fig. 13 shows that with the help of an older plan [Mingazzini and Pfister 1946, Carta III], the observations from the archeological record, and the SfM model the passage in the southern wall could be located and added. The reconstructed water staircase, which no longer exists today, was virtually placed in the rectangular opening in the backwall of the grotto triclinium. The existence of the water staircase can be considered certain due to the elaborate canal system located behind the back wall in the *basis villae* as well as numerous close comparisons in the contemporaneous villa and house architecture of the region [Room 83 in the Casa di Julia Felix, Pompeii II.4.2-12, Rakob 1964; Room 14 in the Villa di Minori, Zarmakoupi 2014, p. 156, Fig.5.5; Room X in the Casa con Ninfeo, Pompeii VIII.2.28, Noack and Lehmann-Hartleben 1936, p. 182-194; Room 31 in the Casa del Bracciale d`Oro, Pompeii VI.17.42, Ciardiello 2006, p. 162-186].

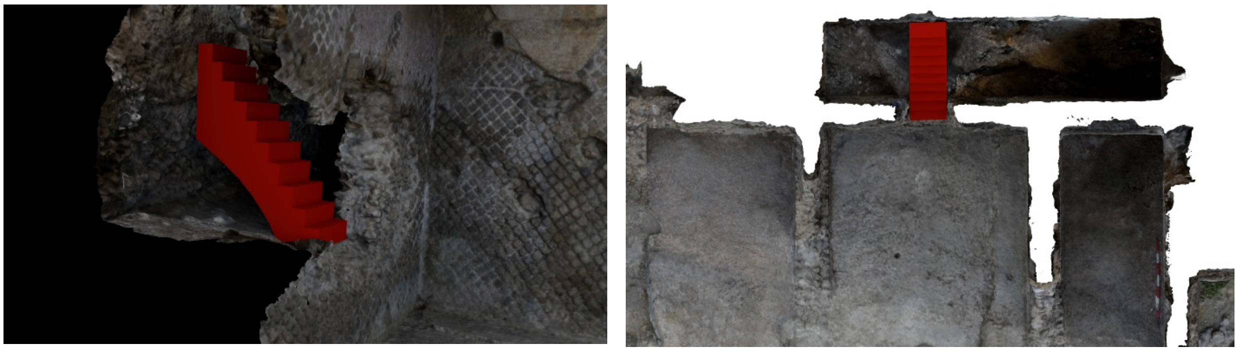
The vault of the room was directly adjusted in height and shape to the dimensions of the SfM model and the lost part was added. This procedure can also be applied to more delicate and decorative elements. The geometric and vegetal stuccowork of the vault was captured by the SfM model and served together with hand-drawn documentation of the decoration, from a time when it was better preserved [Mingazzini and Pfister 1946, Fig. 23], as a template for the reconstruction (Fig. 14).

a *b*

Figure 14. Screenshots of a) the SfM model of the stucco ceiling of the vault b) the partially reconstructed stucco ceiling [S. Götz]

This procedure was carried out on all the extant remains of the triclinium in the north facade. Reconstruction work in three-dimensional space using the 3D graphics software directly on the digitized building proved favorable due to the flexibility in which different architectural forms could be applied, interchanged, revised and adapted. During the modeling process, various proposed solutions for specific areas of the reconstruction can be deployed and discussed experimentally. Different variants of the reconstruction can be proposed on an equal footing, without committing to a specific single end result. Therefore, different versions of archaeologically plausible reconstructions are available for the grotto triclinium, all of which are directly linked to the archaeological record. The possibilities of these mixed methods with the use of 3D techniques are discussed in three examples.

The first example deals with the already mentioned nymphaeum element of the water staircase inserted in the SfM model. This is a virtual copy of the cascade of the very similarly proportioned and equipped grotto triclinium of the Casa di Julia Felix in Pompeii, II.4. 2 - 12. Based on three architectural drawings, consisting of floor plan, section, and elevation it was possible to remodel the water staircase in three dimensions, scale it and insert it into the SfM model of the grotto triclinium at the Cape of Sorrento [Rakob 1964, Figs. 3-5]. The cascade fit easily into the hydraulic small chamber system behind the grotto triclinium, which consisted of two floors. The water staircase completely filled the depth of the chamber system from the back wall to the opening in the wall to the grotto triclinium and stopped at the floor level at the upper chamber, so that the steps descended diagonally from the upper chamber to the threshold of the passage to the grotto triclinium (Fig. 15).

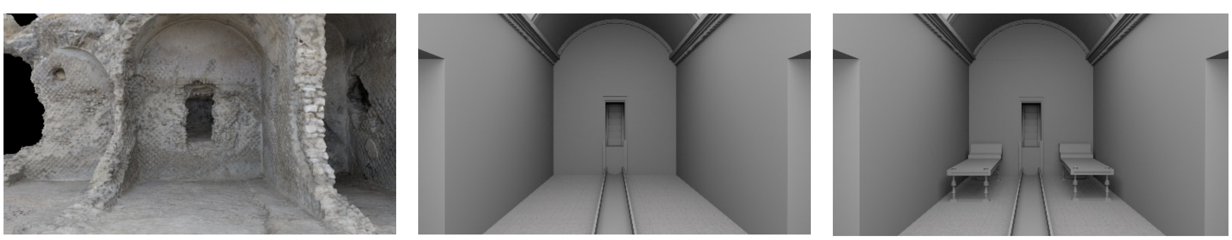


a *b*

Figure 15. Virtual copy of the cascade from the Casa di Julia Felix integrated into the SfM model. a) Side view [S. Götz] b) Top view [S. Götz].

This experiment demonstrates that the empty space in the *basis villae* behind the triclinium was most likely intended for such an elaborate water installation. The experiment conducted in virtual space with the SfM model in combination with the digital copy of an existing ancient cascade from the same cultural, geographic and chronological space supports and visualizes this hypothesis.

In the second example, the different *klinai* were digitally inserted to analyze scale, functionality, and spatial effect. A small channel or *euripus*, which undoubtedly must have once crossed the space similar to the one in Room 16 of Casa dello Scheletro, Herculaneum, III.3 to pass on the water of the cascade, suggests that the *klinai* flanked the channel in the form of a *biclinium* (Fig. 16). This is a similar composition to that in the Casa di Octavius Quartio, Pompeii, II.2.2 [Zanker 1995, p. 155., Fig. 74]. Room *"m"* should technically be called grotto-biclinium, however, the term triclinium is commonly used in archaeology to describe a room in which a symposium could be celebrated and one does not always have to assume three *klinai*. Another *kline* cannot be definitely ruled out, as it could have been placed so that it spanned the reconstructed *euripus*. The virtual positioning of *klinai* can be considered in the 3D model (Fig. 16c).



a *b* *c*

Figure 16. a) SfM model b) Grotto Triclinium reconstruction [S. Götz] c) reconstruction with inserted klinai *[S. Götz].*

Finally, the analyses performed on visual axes and vistas from room *"m"* will be presented. Again, an interaction of SfM model and virtual reconstruction in the three-dimensional space forms the basis for the results of the following investigation. Two different but plausible room sizes with different facade shapes (straight or curved) could be determined for the grotto triclinium with the help of historical photographs from the middle of the 20th century [Russo 2006, p. 59-62]. Also, the visual axis from room *"d"*, located in direct neighborhood of the grotto triclinium to the southwest (Fig. 3) proved to be helpful. This room, unlike all other rooms of the northern facade, was diagonally oriented exactly to the north to allow a special *prospectus* to a group of statues and a fish tank on the rock in front of the *pars maritima* and beyond to ancient Naples [Filser et al. 2017, p. 117-119]. Room *"d"* and the grotto triclinium belong to the same construction phase, so the architectural structures of the grotto triclinium were not allowed to intersect the visual axis of room *"d"*. In the SfM model, this visual axis was traced and the maximum size and positioning of the possible straight facade of the grotto triclinium thus determined (Fig. 17).

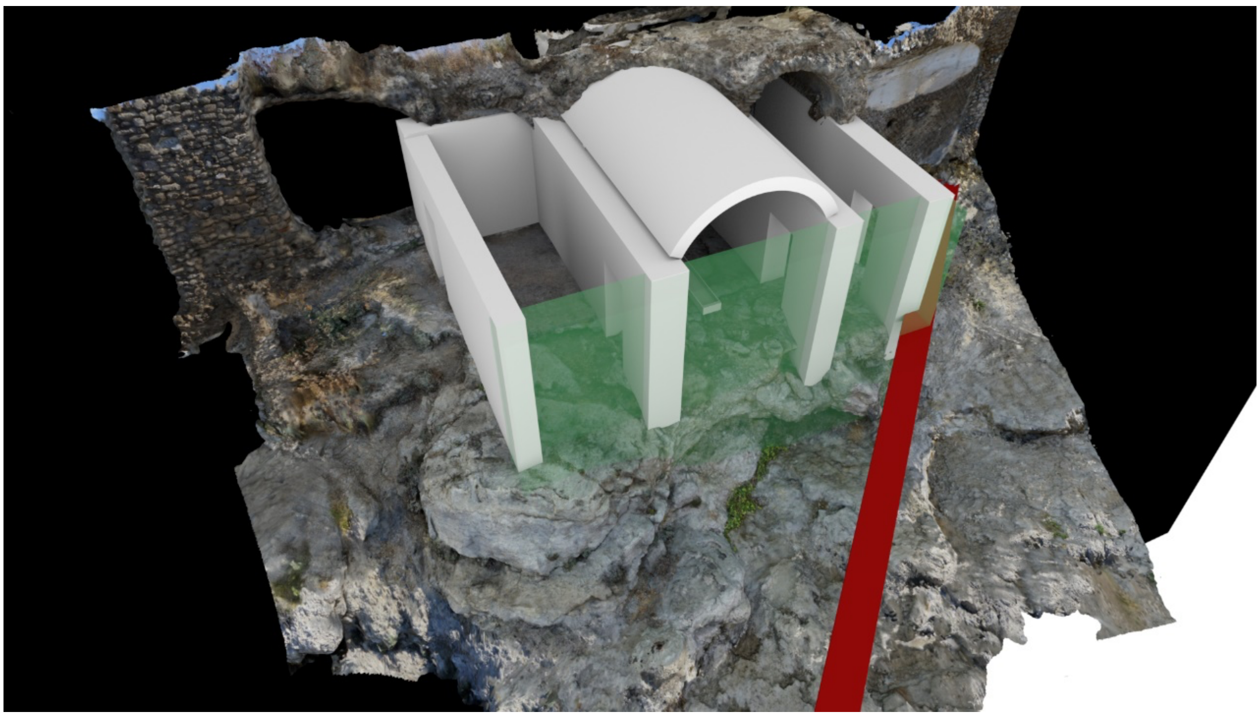
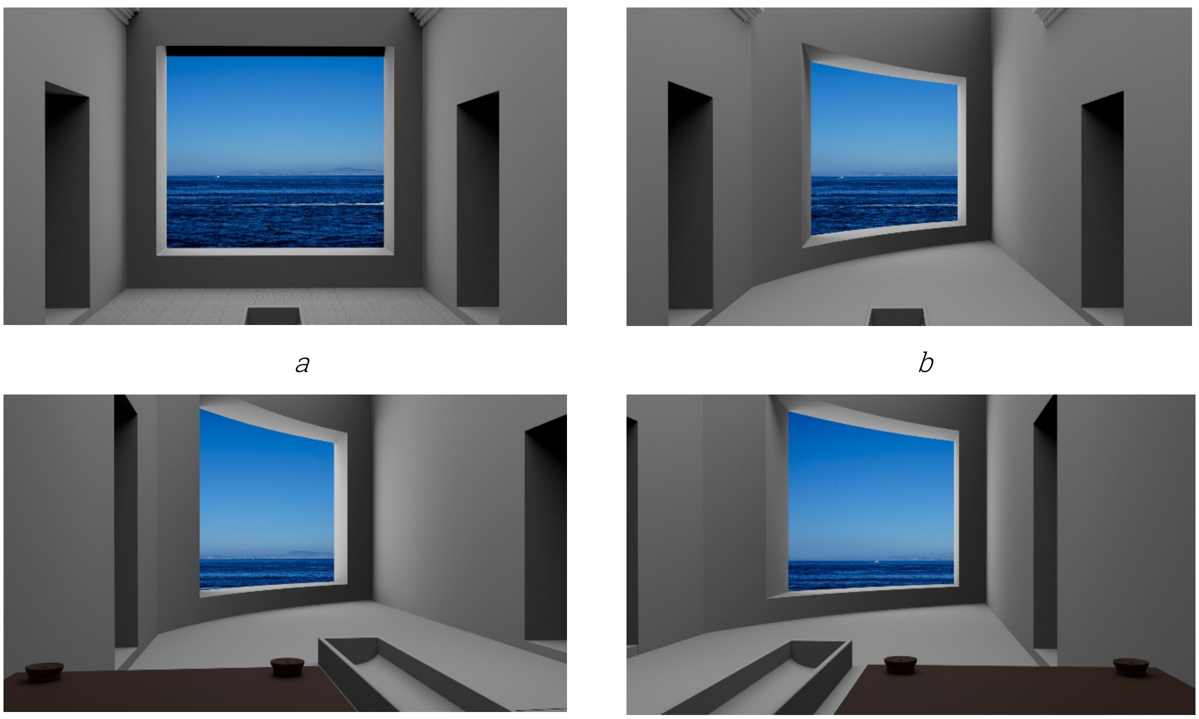


Figure 17. Reconstructed wall courses and vault in the SfM model. Red is the view axis from the neighboring room "d", which must not be crossed by the structures of the grotto triclinium. Green is the area where the facade could be located [S. Götz].

The circularly worked rock in front of the rooms also rather suggests an apsidal facade, which ran along the fringe of the rock. When an apsidal facade is used (Fig. 18b), the SfM model also shows that the visual axis of room *"d"* is not disturbed.

In addition to the implications of the orientation of room *"d"*, analyses were performed to determine the possible *prospectus* from the reconstructed grotto triclinium. The view of Misenum and Puteoli was examined for different room sizes, facade shapes, window openings, and positions in the room. Photographs were taken on site, capturing the present-day view of the coast of the Gulf of Naples from the grotto triclinium. Camera data was documented and the exact positioning (from where in space and at what height the photographs were taken) was marked so that the exact location from which the photographs were taken could be simulated in virtual space using the SfM model. In the SfM model, the positions of the photographs of the Gulf of Naples were transferred one-to-one and the view from the grotto triclinium was virtually reconstructed with the help of camera calibrations. Thus, it was possible to determine how the view of the landscape, so important for villa architecture, changed when parts of the lost architecture were virtually rebuilt in various ways [*prospectus* in Roman architecture: Hales 2003, p. 107-113; Drerup 1959, p. 161-168, 173-174; Lafon 2001, p. 300].



a *b* *c* *d*

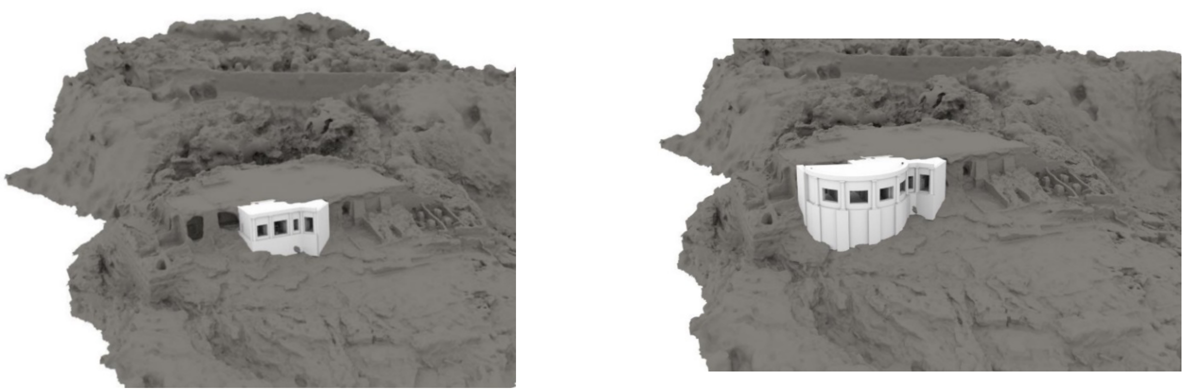
Figure 18. a) View of Misenum and Puteoli through a straight facade with panoramic window; b) view of Misenum and Puteoli through an apsidal façade; c) view through apsidal facade with panoramic window. Position in the southwest: Here Puteoli is very central in the field of view; and d) position in the northeast: Here only Misenum can be seen [S. Götz].

The investigations showed that with both a straight and an apsidal facade, as well as with window openings of different dimensions, the prominent ancient landmarks of Misenum and Puteoli would always have been visible from the grotto triclinium. It becomes particularly interesting when one takes different positions in space and chooses the two hypothetically placed *klinai* as starting points.

It becomes evident how, from different points in space, a different landmark of the gulf was brought into the center of the field of view (Fig. 18). The ancient viewers could see the landmarks on the other side of the gulf even from the back of the room at a distance of up to 10 meters from the opening in the north wall and even through smaller window openings. This suggests that the architectural setting of the room steered the prospectus toward conspicuous landmarks of the Gulf landscape.

In Roman times, the *prospectus* from the grotto triclinium possessed a special view of the Gulf landscape by means of visually controlled architectural staging, which evoked a completely different spatial perception than that which can be inferred from the present-day situation alone. However, the virtual simulation makes it possible to experimentally recreate the veduta-like view through the wall openings in different versions.

These results were obtained thanks to the SfM model and the reconstructions based on it. At the same time, the attempts made with the example of the grotto triclinium of Sorrento show only a fraction of further possibilities in the three-dimensional medium for archaeology and historical building research. Spatial effects, light incidence, lines of sight, visibility and walkways are just some of the many research avenues opened up by combining photogrammetry and 3D reconstruction.



a *b*

Figure 19. SfM overall model (gray) with two different proposals for a plausible virtual reconstruction (white) of the facade of grotto triclinium in the first floor of the villa at the Cape of Sorrento. a) straight façade; b) apsidal facade [S. Götz].

Thanks to today's compatibility and ease of use of various 3D graphics programs, different SfM models can also be compared and connected. The SfM model and the reconstruction from the grotto triclinium could be effortlessly inserted into the overall surface model of the villa at the Cape of Sorrento, with the overall model serving as an additional reference to check the different results again and visualize them in their natural context (Fig. 19). With the help of the overall surface model, which has been continuously expanded since 2015, further parts of the villa can now be virtually reconstructed using the same procedure and new investigations can be attached. It is advantageous, as was done in the case of the grotto triclinium, to reconstruct individual areas of the villa separately and to join them together in the referenced overall model. This way the hardware requirements are minimized, which are necessary for a fluent and effective modeling with accurate results.

Reconstructions of certain areas of the villa are always visualization proposals that, based on the evaluated data, offer one or more possibilities of how the ancient villa architecture might have looked. Thus, a reconstruction never stands alone and without context, but always on an equal footing with other 3D proposals (Fig. 19 a, b). The virtually created 3D reconstructions are always kept in a clear white to distinguish them from the structures still existing today and preserved as SfM models (Fig. 19, 22). The focus here is laid on a scientifically based virtual realization of the form and visual impact of the ancient architecture and not on a reconstruction as real and genuine as possible.

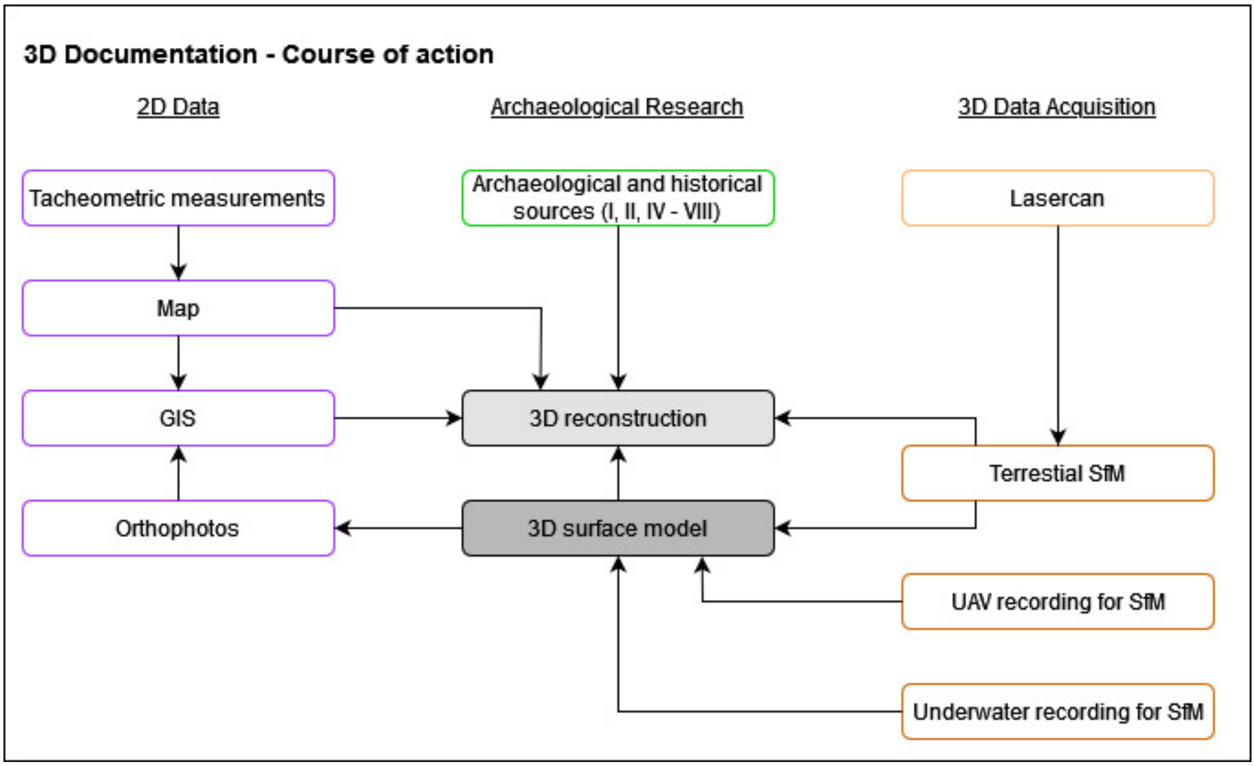


Figure 20. Flow chart of various components for generating a 3D surface model and 3D reconstructions [B. Fritsch].

6. CONCLUSION

By using 3D techniques to document, analyze and interpret the different excavation trenches and relevant features of architecture and landscape (Fig. 21), the research project on the Roman maritime villa of Capo di Sorrento joins the ever-growing list of excavation projects that make extensive use of these methods. In this case, all options were used that were obtainable in the face of changing funding, the availability of the individual participants and the available access to hardware and software. This means that there was no strict open-source policy with regard to the research data, but it also means that it was far from possible to always have unlimited access to commercial solutions. The selection of software products used therefore has been caused by availability. In addition to, the challenging conditions posed by architectural remains and landscape of the study area necessitated the application of various techniques and methods and their regular adaptation of the required 3D methods (Fig. 20).

This is also reflected in the results and data products that emerged in the course of the excavation campaigns and grew along with them. In addition to 'standard products' such as the digital surface model of the entire cape itself, orthophotos generated from 3D models and their integration into the tacheometric plans, two sub-projects stand out:

First, the modeling of the two harbor basins in 3D on the basis of underwater photographs, from which many more insights can be expected in the future, especially in combination with the terrestrial findings. Second, the virtual 3D reconstruction of the grotto triclinium based on SfM models, which provides an excellent insight into the planning and perceptual-aesthetic design of the structure.

The lost ancient architecture partially restored in this way also acts as a virtual basis for a variety of further investigations combining both SfM and reconstruction. In addition to the contextual results, this approach presents a technical challenge. Pointcloud-based SfM models are mixed with NURBS-based reconstructions. This must always be considered in further use of the data. Errors can easily occur due to the different topology, especially in the presentation via online viewers.

Figure 21. Overview of used methods of 3D documentation and reconstruction [B. Fritsch].

A final goal of the project is to present various probable reconstructions of the whole villa complex including the two harbors: The figure published here illustrates one hypothetical proposal of the current state of this on-going work (Fig. 22). Without the different digital methods listed in this paper and their combination with each other and classical field documentation, many possible lines of investigation and resulting findings about the maritime villa would have remained undisclosed. The prudent deployment of each method or a combination of them respectively has led to a more comprehensive understanding of the overall concept of the villa at the Cape of Sorrento and could thus prove to be an example for archaeological field projects to come.

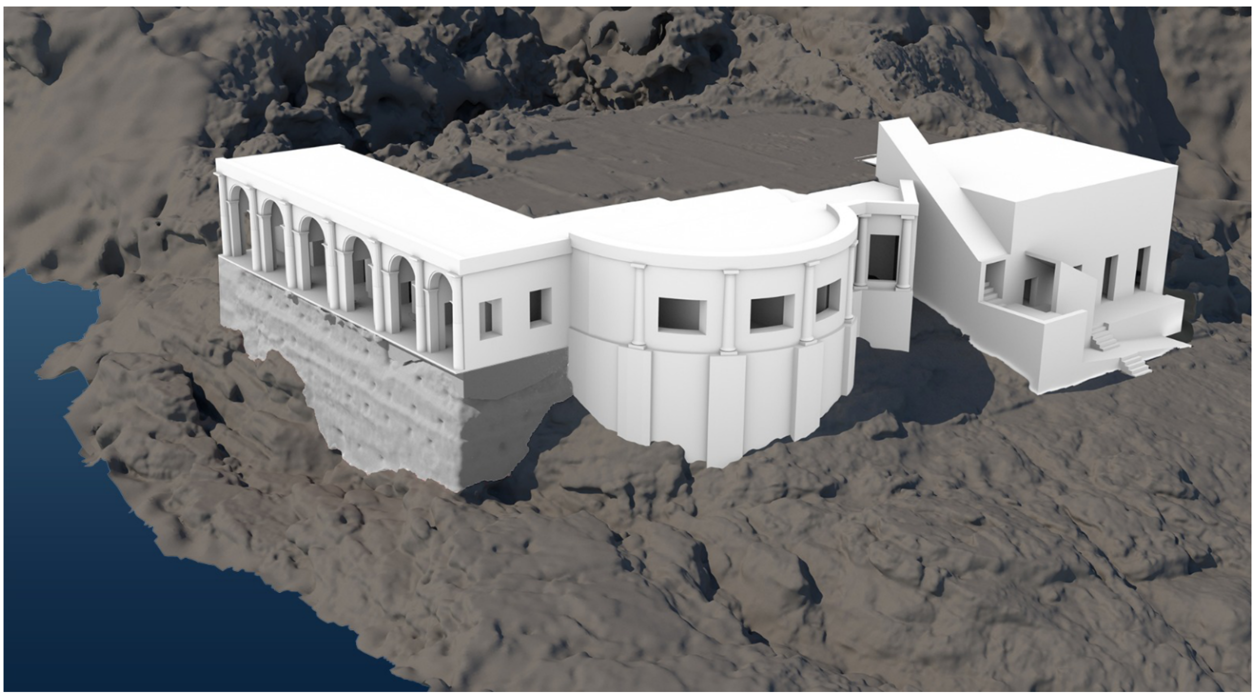


Figure 22. Villa di Capo di Sorrento. Reconstruction of the north and east parts of the first floor of the pars maritima. Work in progress. The brown color shows the natural rock bed, the grey color indicates the existing remains of the facade. The reconstruction part is shown in clear white. [S. Götz, W. Filser].

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Stephan G. Schmid, Wolfgang Filser, Christoph Klose, Rosaria Perrella, Bernhard Fritsch, Will Kennedy, Angelika Walther, Michaela Reinfeld, Giovanna Possenti, Roman Villa of Capo di Sorrento, Edition Topoi, DOI: 10.17171/2-4

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