Fast and detailed digital documentation of archaeological excavations and heritage artifacts

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Abstract: Prompted by the increasing requirement for the fast but precise and detailed digital documentation of archaeological excavations and heritage artifacts, in this article we report our latest experience in capturing detailed 3D geometric information of two sites in Tuscany, Italy, using the image-based approach. We present a 3D recording flow-line, based on multi-image matching, capable of retrieving quickly and precisely all the information needed to document, analyze and visualize excavation sites or archaeological monuments. The 3D modeling method is flexible and can be employed with convergent ground-based or oblique air-photo images, both critical configurations for commercial modeling software.

Keywords: excavation, 3D recording, photogrammetry, multi-image

1 Introduction

Nowadays our cultural heritage is under constant threat and danger. Architectonical structures and sites are threatened by pollution (air pollution, acid rain, birds, etc), tourists, wars as well as environmental disasters like earthquakes or floods or climatic changes. Hidden cultural heritage (under the earth's surface or those partially visible above ground as earthworks, industrial sites, etc.) are affected by agriculture (vineyards, olive cultivation, erosion processes), change of agricultural regimes due to economical change, mining, gravel extraction, contraction of infrastructures (roads, railways), industrial areas and those factors lead to its constant destruction. The available technologies and methodologies for digital recording of archaeological sites and objects are really promising and the whole heritage community is trying to adapt these approaches for fastest, detailed and easy 3D documentations. Indeed 3D modeling could be extremely powerful to improve identification, monitoring, conservation and restoration. At the landscape scales, digital 3D modeling and data analysis allow archaeologists to integrate, without breaks, different archeological features and physical context and better document the area. At the monuments/sites scale, 3D can give accurate measurements and objective documentation as well as a new view under a different point of view. At the artifact scale, 3D modeling allows to reproduce accurate digital/physical replica of every artifact that can be studied, measured, showed, etc. as well as data for general public use, virtual restoration and conservation.

In archaeology the systematic and correct use of 3D (models) for documentation and conservation started just recently but it is still applied in not many case studies for different reasons: (i) the high "cost" of 3D; (ii) the difficulties in achieving good 3D models; (iii) the consideration that it is an optional process of interpretation (an additional "aesthetic" factor); (iv) the difficulty to integrate 3D worlds with other 2D data and documentation; (v) the episodic use of 3D models for scientific analyses.

Nowadays the most common techniques used for 3D modeling are based on images (e.g. photogrammetry) and range data (e.g. active sensors like laser scanners). Both approaches have advantages and disadvantages and generally the choice is done according to the budget, project size, required detail, objectives. Image-based methods (Remondino & El-Hakim, 2006) are widely used for the 3D reconstruction of architectural objects (El-Hakim, 2002) and for the precise modelling of terrain and cities (Gruen, 2000) or monuments and statues (Visnovcova et al. 2001; Gruen et al., 2004). They use projective geometry when the primary goal is visualization or a perspective camera model for more detailed and accurate documentations. They are highly portable and the sensors are generally low priced. On the other hand, range-based methods (Beraldin et al., 2000; Blais, 2004) are based on active sensors that directly capture geometric 3D information of an object using artificial laser light or projecting a pattern onto the object. These instruments recover the 3D information applying different measurement principles like triangulation, time of flight or amplitude modulation. Their costs and problems of transportation, along with the time-consuming and complexity of the related data management, raise often serious problems of practicality in some archaeological sites. In many applications the combination of image- and range-based methods is also realized, in particular for the recording of large architectural objects or complex archaeological sites, where no technique by itself could efficiently and quickly provide a complete and detailed model (Beraldin et al. 2002; Voltolini et al., 2007; Lambers et al. 2007). In the literature comparisons between the different techniques and methodologies are often reported (Böhler & Marbs, 2004; Kadobayashi et al., 2004; Böhler, 2005; Remondino et al., 2005).

In this paper we want to give an overview of the image-based modeling method describing in particular photogrammetry as an essential and important technique for the 3D documentation, reconstruction and interpretation process in the archaeological field. We present a newly developed multi-image matching algorithm and its performances using ground-based and oblique aerial images. As case studies we report an excavation site and an heritage area in Tuscany, Italy.

2 Image-based approach in terrestrial applications

Compared to other recording and modeling methods, images can be acquired with inexpensive systems and contain all the information for the generation of a textured 3D model. But deriving a complete, detailed, accurate and realistic 3D image-based model is still a difficult task, in particular for large or complex objects, if the images are acquired by non-experts or if uncalibrated or widely separated images are used. According to the project requirements, automated, semi-automated or manual image-based approaches should be employed to produce digital models usable for inspections, visualization or documentation. 3D image-based modeling methods can be classified according to the level of automation or the required input data while their strength is reflected by the variety of scene that can be processed and the level of detail that can be reconstructed. The entire photogrammetric workflow used to derive metric and reliable information of a scene from a set of images consists of (i) calibration and orientation, (ii) 3D measurements e.g. via image matching, (iii) structuring and modeling, (iv) texture mapping and visualization. For a review of the entire image-based modeling pipeline we refer to (Remondino & El-Hakim, 2006).

Since many years photogrammetry is dealing with the precise 3D reconstruction of objects from images. Even if it often considered as time consuming and complicated, the heritage community is starting to consider it for digital documentation also at terrestrial scale as a very promising alternative to range sensors, traditionally used as easy and efficient instruments, even if not always portable and usable. Photogrammetry requires precise calibration and orientation procedures, but different commercial packages are nowadays available. In the terrestrial case, those packages are all based on manual or semi-automated measurements. They allow, after the (manual) tie point measurement and bundle adjustment phase, to obtain sensor calibration and orientation data, 3D object point coordinates from a multi-image network, as well as wireframe or textured 3D models. Nevertheless two great research topics are still largely investigated: (i) the automated image orientation and (ii) the dense surface measurement. Indeed, at the moment, no commercial solution is able to perform an automated markerless image orientation while automated camera calibration based on coded-target is an issue already solved since some years (Gangi & Hanley, 1998; Cronk et al., 2006). Furthermore, there is no package able to automatically reconstruct a complex surface model employing more than two images: indeed commercial photogrammetric software have only a matching tool able to provide dense surface model from stereo-pairs (Kadobayashi et al., 2004; Chandler et al., 2007) while a multi-photo approach able to treat convergent images would be more reliable and efficient.

Fully automated 3D modeling procedures have been also widely reported in the vision research community (Pollefeys et al., 2004), even if they generally produce results which are mainly good for simple real-time 3D recording and quick visualization The key to the success of these fully automated approaches is the very short interval between consecutive images, the absence of illumination or scale changes and the good texture in the images. These are all constraints that cannot always be satisfied during the image acquisition (Voltolini et al., 2006), in particular the small baseline. Moreover illumination changes can always appear in a sequence as well as image-scale differences. To face the wide baseline and the image-scale problems, different strategies have been proposed (Lowe, 2004; Mikolajczyk et al., 2005), although further research in this area is still needed. Indeed their reliability and applicability for automated image-based modeling of complex objects is still not satisfactory, as they yield mainly a sparse set of matched feature points. Automated dense reconstruction were instead presented in (Strecha et al., 2003; Megyesi & Chetverikov, 2004), but no accuracy tests were reported.

In some applications, manual measurements are also performed, generally for complex architectural objects or in cultural heritage documentations where highly precise and detailed results are required (Gruen et al., 2004). Manual measurements are time consuming and provide for less dense 3D point clouds, but have higher reliability compared to automated procedures. Therefore, the modeling steps are generally separated, having automation where possible and interaction where reliability and precision are necessary.

In the following section, the surface measurement approach developed at ETH to derive dense and detailed 3D model from images is presented. It is based on the precise least squares measurement method (Gruen, 1985) and is able to employ multiple images (>2) at the same time.

3 Dense, accurate and detailed 3D modeling

For a precise documentation and 3D modeling of sites or objects, images should be acquired under a certain acquisition rules and with a calibrated camera (otherwise calibrated afterwards in the lab at the same settings used on the field). After the image orientation phase to recover the camera poses, the surface measurement step can start to extract (dense) 3D point clouds of the investigated area. This phase is generally performed using manual procedure if an architectural or very complex object is surveyed. Indeed, the former needs only few points to recover the 3D geometry by means of lines and planar surface, the latter need the user interaction and recognition to derive correct 3D results (Figure 1).

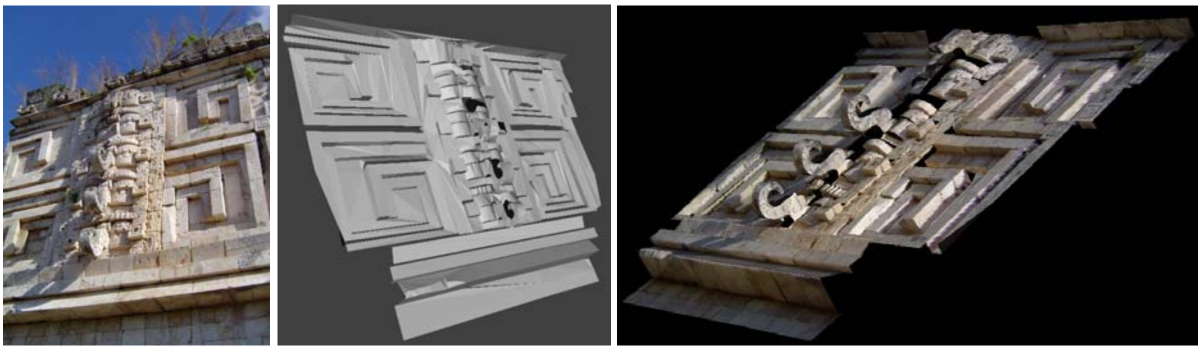

Figure 1: Very complex heritage object (Uxmal, Mexico) which must be measured and modeled manually to correctly reconstruct all the detailed parts.

On the other hand, for landscape, excavation areas and most of the heritage objects, automated procedures can be employed for a reliable generation of a dense digital surface model. With this purpose, we have developed a procedure able to derive detailed and accurate surface model from any kind of set of images. It is a multi-image matching, originally developed for the processing of the very high-resolution TLS Linear Array images (Gruen & Zhang, 2003) and afterwards modified to accommodate any linear array sensor (Zhang & Gruen, 2004; Zhang, 2005). The matcher has been then extended to process other image data such as the traditional aerial photos or convergent close-range images (Remondino & Zhang, 2006; Lambers et al., 2007). It is based on the Multi-Photo Geometrically Constrained (MPGC) matching concept (Gruen & Baltsavias, 1986) and the Least Squares B-Spline Snakes (LSB-Snakes) method (Gruen & Li, 1996). After an image pre-processing for noise reduction and radiometric optimization, different levels of image-pyramids are generated. The matching is then based on three different primitives and is thought to be a robust hybrid method which takes advantage of both area-based and feature-based matching techniques using local and global image information. In particular, it combines an edge matching method with a (feature and interest) point matching method through a probability relaxation-based relational matching process. Feature points are suitable to generate dense and accurate surface models but they suffer from problems caused by image noise, occlusions and discontinuities. Edges generate coarser but more stable models as they have higher semantic information and they are more tolerant to image noise. The combination of both leads to very successful results. The approach does not aim at pure image-to-image matching but it directly seeks for image-to-object correspondences. A point is matched simultaneously in all the images where it is visible and, exploiting the collinearity constraint, the 3D coordinates are directly computed, together with their accuracy values. Exploiting the multi-image concept, highly redundant matching results are obtained, compared to classical stereo approaches. The high redundancy also allows automatic blunder detection. Mismatches can be detected and deleted through the analysis and consistency checking within a small neighbourhood. A part from the known camera parameters, the matcher requires some seed points between the images to start the automated matching procedure. These points can be measured manually in mono or stereo-view as well as imported from the orientation phase.

The accuracy of the method have been demonstrated in different works (El-Hakim et al., 2007; Rizzi et al., 2007) showing how the matcher is able to retrieve 3D results very similar to range sensors.

In the following paragraphs, experiences with archaeological excavation areas and objects are reported and commented.

4 Examples

Our first case study focuses on the excavation of a late antiquity-early medieval church at Pava in the province of Siena, Italy (Figure 2). The site has been identified through the integration of archaeological/geophysical fieldwork (Campana & Francovich, 2005) and documents relating to a dispute between the bishops of Siena and Arezzo in 714-715 AD which indicate the existence of the parish church of ‘San Pietro in Pava’ (Schiaparelli 1929). The exegesis of the documents allows us to surmise the earlier existence of a cult shrine building. We also know that San Pietro in Pava stood close to the River Asso, in the locality named in the Extent of 1320 as ‘Pieve Vecchia’, not far from the present-day Pieve a Pava. The building is again attested in 1029, though by this time it was probably reduced to a ruin, abandoned and replaced by the nearby sister church of Santa Maria in Pava, which in 1045 appears in the documents under the title of ‘pieve’. However, other documents record that it was still the responsibility in 1320 of the rector “Ser Finus presbiter plebis Pievevecchia”. Nowadays, the excavated area measures approximately 40x30 m. A very big parish church (33 metre long by 10 metre) was found, characterized by a peculiar plan, double abse, the first one on the east and the second one on the west part of the church (Campana et al. 2006). During a documentation flight with a light aircraft (Cessna 172), a set of oblique air photographs were acquired, using a Canon EOS 20D consumer grade digital camera (8 Mega pixel, 6.4 micron pixel size). As the image acquisition was not done with the final goal of modeling in 3D the excavation site, different focal settings were used, mainly 47 mm, 53 mm, 60 mm and 135 mm. This fact generated a nice set of documentation images around the site, but with all different camera interior parameters, conditions not really favourable for easy and precise modeling. Nevertheless, we were able to orient a group of 5 images (average footprint ca 2 cm) and apply our matcher to produce a dense digital surface model (DSM) of the excavation. Approximately 5 million points were obtained in ca 3 hours of work, afterwards meshed and contours derived (Figure 3).

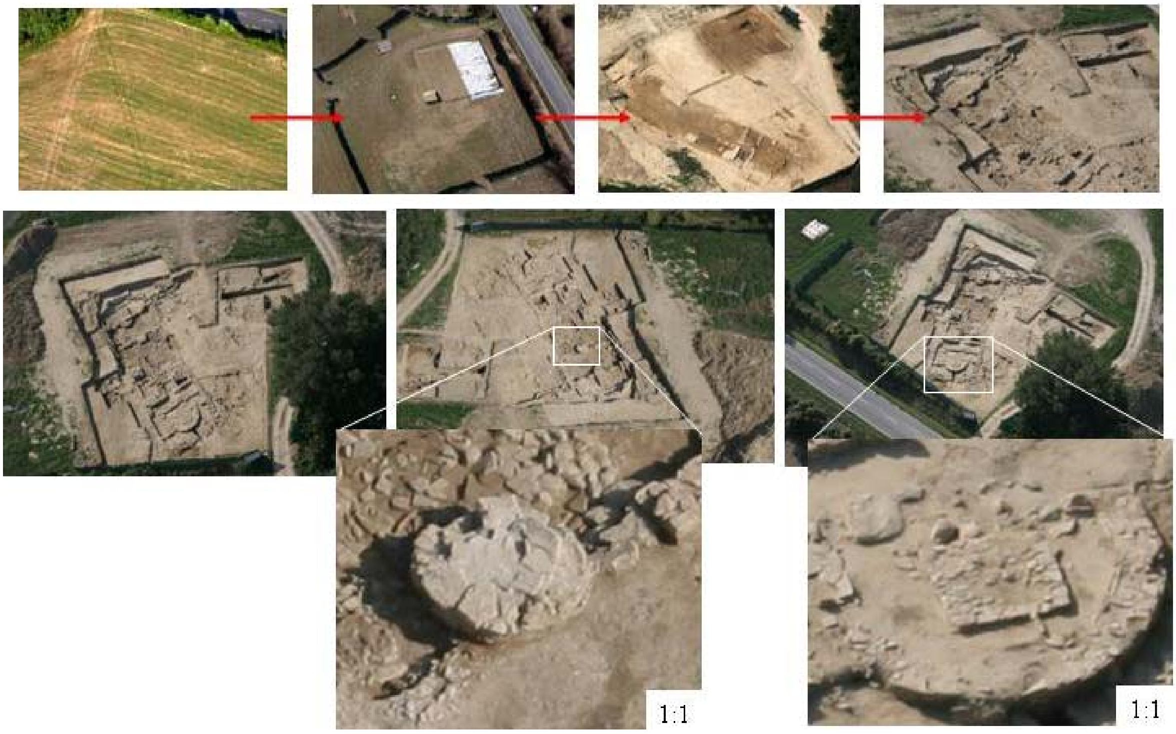

Figure 2: The excavation area of Pava (40x30m) near Siena (Italy) from the original inspection through the first excavations and actual situation. The aerial images have been acquired for simple documentation without any planning for 3D modeling. A zoom 1:1 of the details is also presented.

The second study relates to a masonry castle on the coast near Piombino (Italy), excavated by the University of Siena in the 1980s. Here, we generated a 3D model of the defensive walls and some of the buildings in the interior using ground-based photographs. As it is possible to see in figure 4, it is quite hard to get close to the monument because of the rocky and steep morphology of the site. Here, the goal was to test whether images could be the right and easiest solution to document some detailed parts of the archaeological site. In particular, a part of the wall of the castle and the interior of an old church were selected.

We generated a 3D model of the defensive walls using three images acquired with a simple, portable and very cheap digital camera. The derived DSM (Figure 5) is pretty detailed and the single elements of the wall are well recognizable.

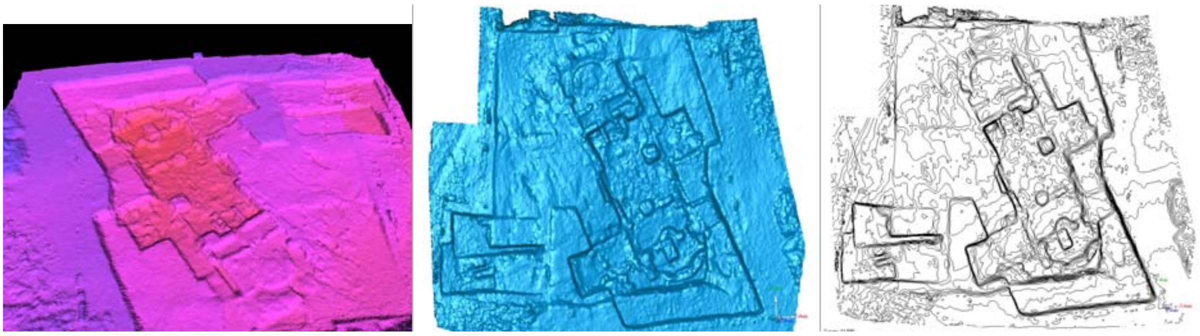

Figure 3: DSM of the excavation site derived using amateur oblique aerial images visualized as colour- and shaded mode. The generated contours have an interval of 5 cm.

Figure 4: S.Silvestro rock near Piombino (Italy) and the detailed 3D modeling of its rock walls, simply from 3 convergent images acquired with a consumer grade digital camera with 6 Mega pixels.

Furthermore we modeled the abse of the church deriving, also in this case, a pretty detailed DSM (Figure 5). In this case, the church walls could be easily modeled using few points and geometric entities. Nevertheless the use of dense surface model could be very useful to study the stratigraphic pattern of the wall, architectonic details, to produce restoration plans, etc.

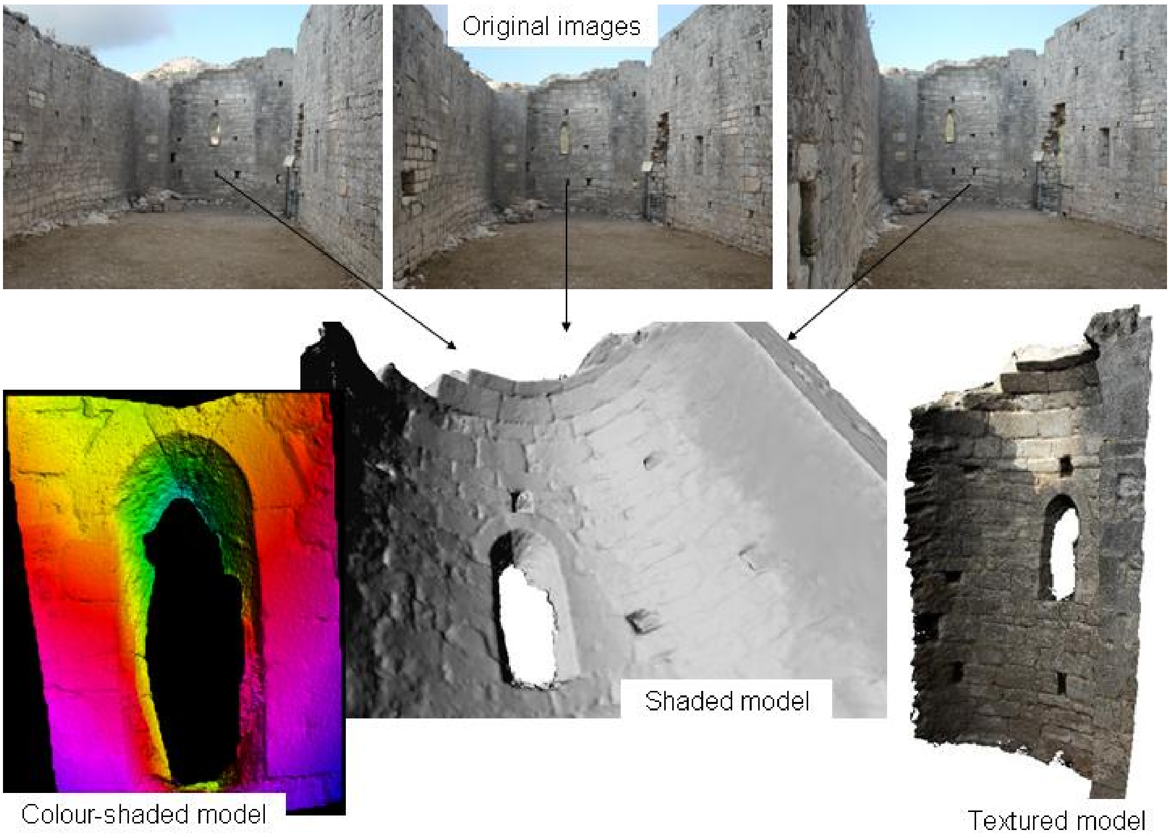

Figure 5: The interior of a church, modeled using three convergent images.

5 Considerations, conclusions and outlook

The balance of the last decades of archaeological research in the use of 3D digital documentation/representation in terms of scientific investigation is quite disappointing if we think at the possibility offered nowadays by newly developed software and hardware. The use of 3D images was typically oriented to suggest final reconstructions and not to contribute to scientific interpretation. In this situation, definitively, there is a striking contradiction considered that it is possible to represent every feature of the material culture thought three spatial coordinates. The third dimension is a fundamental part of the reality. Nowadays we have the opportunity to record it from space scale to the individual site and last to the artefact. 3D should constitute a bridge between knowledge and communication. It is remarkable to say that archaeological excavations using 3D technologies in the phases of acquisition and reconstruction are still a few. Therefore the documentation process is fragmented in many different ontologies (totally analog, partially digital and analog), where the 3D information is often missing. In the following key points it is possible to summarize benefits and properties of the 3D digital world in archaeology:

- Interaction: a 3D model involves a high degree of interaction.
- Difference: the representation in 3D produces more difference in cybernetic sense; interacting with 3D data we develop a major exchange of information.
- Spatial relationships: 3D spatial features visualize, model and develop relations generally not identifiable in 2D space
- Multi-modality: 3D interaction stimulates our cognitive system to adapt and follow the spatial coordinates of reference, in scale and size.
- Light: 3D interaction and movement involves changes of the light and shadow conditions of the reconstructed model so that a better perception and also interpretation is achieved.
- Geometry: the more complex is the geometry of an object the more we have a capacity of analysis.
- Transparency: the reconstructive processing of information can be validated and shown by a sequence of 3D spatial maps in overlay or different representations.
- Multimodality: 3D information allows a multimodal and multi-sensorial interaction with the 3D model.
- Connectivity: each 3D spatial information multiplies in a conceptual network of links its communication model.
- Preservation: 3D digital data are useful for site/object documentation and storage in case of lost of destruction.
- Fruition: a 3D model can be exchanged between users or used in virtual museum for people who cannot visit the real site.

We demonstrated how accurate and detailed 3D results can be almost easily derived using simple cameras. Of course active sensors allow a relative rapid acquisition of a large quantity of 3D information but we must point out that the costs of the equipment and the problems of transportation, along with the complexity of the related data management, raise serious problems of practicality in many archaeological missions. Therefore, as an alternative, we argue that images acquired with low-cost digital cameras (or even mobile phones), by non-specialist research workers, can be used to create realistic 3D models, with good geometric detail by applying appropriate image-processing algorithms.

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