ASSESSING THE PERFORMANCE OF A STRUCTURED LIGHT SCANNER

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ABSTRACT:

An alternative to the mostly known and market dominating laser scanners are Structured Light scanners. Structured light 3D scanners project a pattern of light on the object and detect the deformation of the pattern on the object. They are basically non-contact optical systems, based almost entirely on the principles of photogrammetry in order to transform image pairs to surface information. They are able to achieve information of very high density and of very high accuracy.
For assessing the capabilities of such a system under real working conditions some tests were performed and their results are analysed and presented in this paper. Among others, industrial prototype gauges served as test objects, with their dimensions known at very high accuracy. Suitable mesh densities were implemented for deriving the objects' surface. They were measured and compared to the nominal values. In addition, the system was put to test under several ambient conditions, i.e. natural sunlight and indoor lighting, and using various object materials, like marble, wood, stone etc., in order to assess its qualitative performance.
Reference is also made in the paper to several practical applications of the system, in order to demonstrate its range of applicability. Special interest is given in processing aspects for the creation and visualization of detailed photorealistic 3D models. Various well known open issues in the related processes are identified and the respective solutions/significant improvements in the workflow pipeline brought by the employment of new technologies are highlighted. The software used is described and high resolution visualizations of sub-millimeter accuracy for each case study are presented and assessed based on completeness, accuracy and ease of processing. Finally, conclusions are drawn concerning the usage of the hardware and software components of the system, but also its performance characteristics. The practical results are discussed and evaluated based on the experience gained through these applications.

1. INTRODUCTION

Accurate representation of objects, large and small, has been in the forefront of scientific interest for as long as the specialists felt the need for studying those objects. Two-dimensional representations using rules and techniques of projective and descriptive geometry have been common practice for centuries. It was from these 2D representations that three-dimensional information ought to be extracted. This task required special education, hard practice, skill and imagination. Nowadays these techniques have been replaced by digital scanning which is achieved using 3D scanners.

A **3D scanner** is a device that analyzes a real-world object or environment to collect data on its shape and possibly its appearance (i.e. color). The collected data can then be used to construct digital, three dimensional models useful for a wide variety of applications.

Digital scanning of objects has been common practice for more than a decade. Laser technology has been the flagship of this activity, but other means of acquiring 3D information of an object's surface have also been used widely. Modulated light scanners, non-contact passive scanners, photometric systems and silhouette scanners are the most known kinds of systems acquiring vast numbers of points describing the surface of interest. All these systems work at different rates, at various densities and at different accuracies, hence each one serves special needs in the market.

The final product of digital scanning methods is, of course, point clouds of varying densities and accuracies. Processing of these point clouds involves the implementation of a multitude of software and techniques, in order to produce 3D meshes, 3D surface models and, finally, 3D rendered models of varying resolutions.

Digital scanning has been used extensively in many applications, such as Cultural Heritage documentation, industrial applications and design, automotive industry, orthodontics and prosthetics, reverse engineering and prototyping, quality control and inspection and -of course- in the entertainment industry for the production of movies and video games (e.g., Teutsch, 2007; Rocchini et al., 2001).

2. DIGITAL SCANNING METHODS

Many different technologies have been used to build various 3D scanning devices; each system comes with its own limitations, advantages and costs. It should be noted that many restrictions are due to the properties of the various objects that are to be digitized: for example it is almost impossible to acquire 3D information from shiny, reflective or transparent objects with optical systems. Hence depending on the properties of the objects of interest and on the aim of the final product various alternative 3D scanning systems have been developed. Some of the most widespread technologies of 3D data acquisition are

briefly mentioned in the following (http://en.wikipedia.org/wiki/3D_scanner).

Modulated light: Modulated light 3D scanners shine a continuously changing light at the subject. Usually the light source simply cycles its amplitude in a sinusoidal pattern. A camera detects the reflected light and the amount by which the pattern is shifted, determines the distance the light has travelled. Modulated light also allows the scanner to ignore light from sources other than a laser, so there is no interference.

Non-contact passive: Passive scanners do not emit any kind of radiation themselves, but instead rely on detecting reflected ambient radiation. Most scanners of this type detect visible light because it is a readily available ambient radiation. Other types of radiation, such as infrared could also be used. Passive methods can be very cheap, because in most cases they do not need particular hardware.

Photometric: Photometric systems usually use a single camera, but take multiple images under varying lighting conditions. These techniques attempt to invert the image formation model in order to recover the surface orientation at each pixel.

Silhouette: These types of 3D scanners use outlines created from a sequence of photographs around a three-dimensional object against a well contrasted background. These silhouettes are extruded and intersected to form the visual hull approximation of the object. With these kinds of techniques some kind of concavities of an object (like the interior of a bowl) are not detected.

Apart from the above, the market has been filled with various systems capable of acquiring 3D point clouds directly from the object, using laser technology. Better known are the **Terrestrial Laser Scanners** initially developed to survey as-built complex industrial structures, and later found great application in monuments and Cultural Heritage objects in general. These TLS systems are based on the concept of determining the time of travel of a laser beam from the instrument to the object, in order to determine the position of the targeted point. Time-of-flight or triangulation laser scanners are the most known specimens of this kind of instruments.

Time-of-flight and triangulation range finders each have strengths and weaknesses that make them suitable for different situations. The advantage of time-of-flight range finders is that they are capable of operating over very long distances, in some cases more than a kilometer. These scanners are thus suitable for scanning large structures like buildings or geographic features. The disadvantage of time-of-flight range finders is their restricted accuracy. Due to the high speed of light, timing the round-trip time is difficult and the accuracy of the distance measurement is relatively low, i.e. in the order of millimeters. Triangulation range finders are exactly the opposite. They have a limited range of some meters, but their accuracy is relatively high. The accuracy of triangulation range finders is on the order of tens of micrometers.

At a rate of, e.g., 10.000 sample points per second, low resolution scans can take less than a second, but high resolution scans, requiring millions of samples, can take minutes for some time-of-flight scanners. One serious problem that arises in this case is distortion from motion. Since each point is sampled at a different time, any motion in the subject or the scanner will distort the collected data. Thus, it is usually necessary to mount both the subject and the scanner on stable platforms and minimize vibration. Using these scanners to scan objects in motion is very difficult, but not impossible.

3. STRUCTURED LIGHT SCANNNERS

3.1 Principle

As already mentioned, an alternative to laser scanners are Structured Light scanners. Structured light 3D scanners project a pattern of light on the subject and detect the deformation of the pattern on the subject. The pattern may be one dimensional or two dimensional. An example of a one dimensional pattern is a line. The line is projected onto the subject using either an LCD projector or a sweeping laser. A camera, offset slightly from the pattern projector, records the shape of the line at an angle α (Figure 1) and a technique similar to the triangulation principle is used to calculate the distance of every point on the line. In the case of a single-line pattern, the line is swept across the field of view to gather distance information one strip at a time.
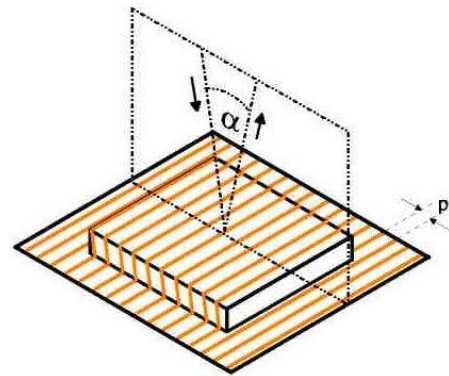

Figure 1: The triangulation principle

An example of a two dimensional pattern is a grid or a line strip pattern. A camera is used to record the deformation of the pattern and a fairly complex algorithm is used to calculate the distance at each point in the pattern (Figure 2). One reason for this complexity is ambiguity. The advantage of structured light 3D scanners is speed. Instead of scanning one point at a time, structured light scanners scan multiple points or the entire field of view at once. This reduces or eliminates the problem of distortion from motion. Some systems that employ such methods enable the scanning of moving objects in real-time. In most cases such systems have a relatively narrow field of view that may range from a few centimeters to a couple of meters, based on the components of the system and the calibration process.

Recently, Zhang & Huang (2006) developed a real-time scanner using digital fringe projection and phase-shifting technique, a somewhat different structured light method. The system is able to capture, reconstruct and render the high-density details of the dynamically deformable objects, such as facial expressions, at 40 frames per second.
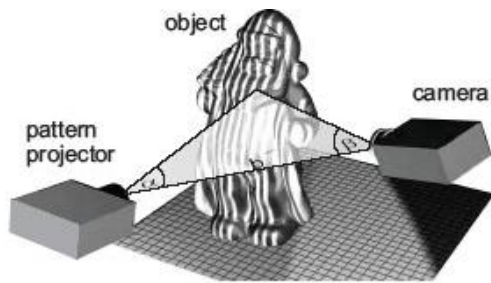
Figure 2: The two dimensional pattern scanner (Teutsch, 2007)

3.2 The XYZRGB® SL2 Scanner

Recently the laboratory of Photogrammetry of National Technical University of Athens, Greece, has acquired a Structured Light Scanner, the SL2 system by XYZRGB Inc. The system is comprised of low cost off-the-shelf hardware. Two Canon 450D digital SLR cameras of 12MP and alternatively two machine vision cameras (uEye 5MP) mounted on a rigid base take up the role of image pair acquisition. A DLP projector (Infocus IN35W) is used to project the necessary structured light alternations and the whole system, including supportive tripods, is operated through a standard Laptop running the XYZRGB proprietary software. The distance between the cameras, i.e. the base, may be varied, according to the size of the object of interest and to its distance from the cameras. The system is driven via a laptop with proprietary software that carries out the required processing for the structured light data (Figure 3). This software takes care of the camera and projector smooth coordination. It provides for the necessary setup calibration, which includes both camera geometry parameters and also relative positioning of the image acquisition set with the help of a suitable checkerboard.

Figure 3: The main components of the SL2 scanner

The fact that this system employs two cameras is clearly an advantage. The workflow of the system requires a calibration sequence and after that it is ready to acquire the data for producing the 3D information. The calibration procedure determines both the interior orientation parameters of the cameras and their relative position and the scale of acquisition. For this purpose a custom calibration board, a simple checkered board, is imaged at various angles by both cameras (Figure 4). The software then calculates the various parameters and the system is ready for use. A series of calibration boards with different physical and square sizes is provided, in order to cover various taking distances. The larger the distance, the bigger calibration board is obviously necessary.

The calibration procedure theoretically needs a few minutes to be completed but in practice it is proven that it takes something between 20-40 minutes for each new setup, depending on the ambient conditions, i.e. taking distance, lighting etc.
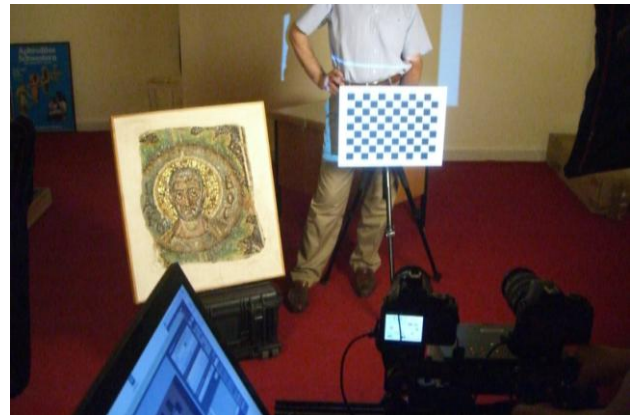

Figure 4: SL2 Scanner calibration

After the setup calibration, the software drives the cameras for the main data acquisition phase.

Scanning with the SL2 system actually involves the acquisition of 8 consecutive image pairs, as patterns of light are projected onto the object in sequence (Figure 5). These patterns are alternating black and white stripes with decreasing width. Based on the distortion of theses stripes on the object as they are imaged on both images of the stereopair, the software later calculates a triangular mesh of the object's surface, on which the texture may be projected. The system calculates depth by the exploitation of the distortion of these patterns on the surface of the object, following the triangulation principle, only in this case two cameras are employed. The result is a dense (up to 150μm) mesh of triangles, with points on the objects surface (Figure 6).

Figure 5: Projected structured light during data acquisition

Once the system has been calibrated, scanning is fast and reliable. However, the results are highly dependent on the behaviour of light on the surface of the object and great care should be given to the imaging parameters of the cameras. The use of suitable polarizing filters both for the projector and for the cameras is recommended.
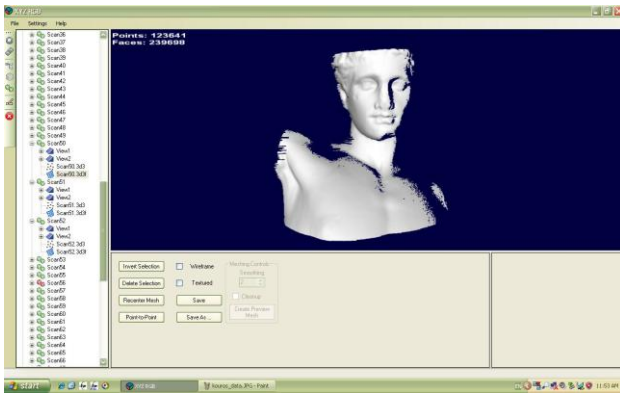
Figure 6: The resulting 3D mesh

Depending on the complexity of the object's surface, on its size and on the required density and final accuracy, a considerable number of individual scans may be necessary to cover the object. Using GSM, a piece of 3D processing software that is also included in the bundled software, mesh registration is very fast, precise and easy. However, further processing for visualization or rendering requires use of other more specific software, such as 3D Studio Max, Geomagic, Maya etc.

4. PERFORMANCE OF THE SL2 SYSTEM

4.1 Performance on different materials

According to the manufacturers the system is claimed to be able to scan objects up to 2x2m. However, full resolution is achieved at much closer ranges. For its performance correct focusing is very critical and lighting conditions play a key role, with bright sunlight being forbidden. Another important factor for the quality of the results is the material of the surface of the object. Highly reflective materials, e.g. silver and gold, as well as light absorbing ones, e.g. marble, pose severe problems and the results may be disappointing. The manufacturers of SL2 scanner system claim a density capability of 150 microns and an accuracy of 50 microns.

So far the system has been practically tested on various materials, on the occasion of several implementations. Materials which do not absorb light, i.e. they reflect most of the incident radiation, perform well with the SL2 system. Wood and matt clay surfaces provide excellent specimens for use with the structured light systems. If the surface is painted, it should not be with a glossy paint and definitely not gold or silver. In such cases, even if the base material is suitable, the results tend to be disappointing (Figures 7 & 8). On the other hand silver and gold plated (Figure 4) objects present great difficulties. The main problem is the light reflections on the object. This may be overcome with the use of polarizing filters, both on the projector and on the lenses of the cameras. However, this is not always a successful task, thus making the scanning of such objects very difficult and unreliable. An example of a difficult shiny silver object is shown in Figures 9 & 10. It is a silver ancient bracelet depicting a snake.

Marble, on the other hand, presents peculiar performance. Depending on its chemical and structural composition, i.e. its crystalline properties, it absorbs and at the same time reflects incident light.

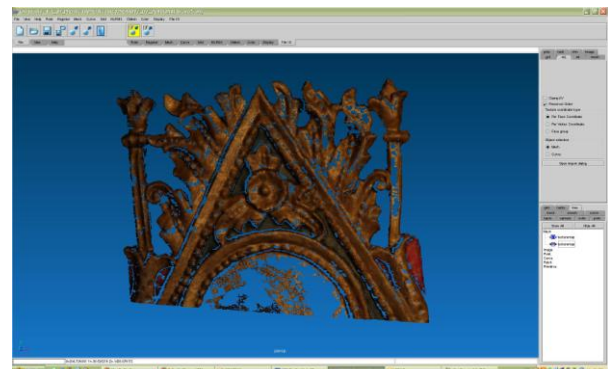Figure 7: An actual image of a gold painted artifact

Figure 8: The resulting incomplete 3D mesh on the shiny parts of the object of Figure 7
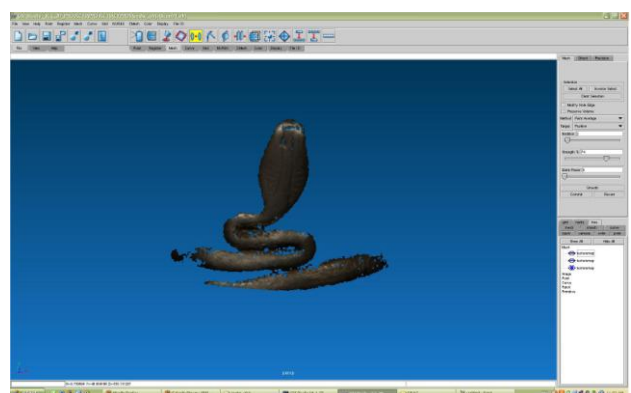

Figure 9: A silver bracelet

Figure 10: The incomplete 3D mesh of the object of Figure 9

An example of a plaster object performing satisfactorily is the copy statue of a young athlete (Figure 11), while the statue of the Aphrodite (Figure 12) performs in a completely different manner.
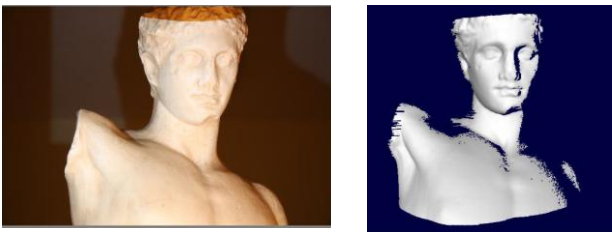
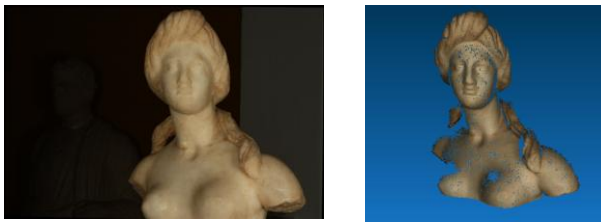Figure 11: Example of a plaster object with satisfactory results

Figure 12: Example of a marble object with unsatisfactory results

It is obvious for the above tests that the material is of utmost importance for the final performance of the SL2 system, as indeed for any structured light scanner. Needless to stress that if the ambient light is strong, the system will be unable to record useful raw data. Hence it is preferable to work in controlled lighting conditions and, if possible, to provide the required artificial light with the use of e.g. a studio flash system (Figure 13).

Figure 13: The setup of the SL2 scanner

4.2 Accuracy tests

For assessing the spatial accuracy of the XYZRGB® SL2 system special objects of known dimensions were scanned. These were industrial prototype gauges of the Metrotechnics Laboratory of NTUA, which were of known and officially certified length (Figure 14). The largest available gauges were used, two metal bars of parallelepiped shape of 80mm and 100mm lengths. A certificate of a recent calibration of the two bars gave the following data for their lengths:

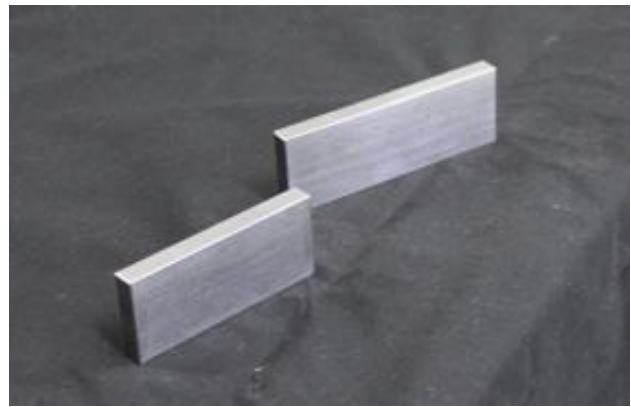| Gauge (nom. Value)	Length (mm)	Precision (mm)
01-80	80.00015	0.00010
01-100	100.00005	0.00011

Figure 14: The two industrial gauges used for the accuracy tests

Scanning of these two gauges with the SL2 system was not an easy task for the reasons explained in the previous section. The metallic surface of the two gauges presented severe difficulties and the first tests were very disappointing. The solution was given by spraying the gauges with thin powder (Figure 15), in order to reduce the undesirable reflections and provide the system with some texture for calculating the meshes.
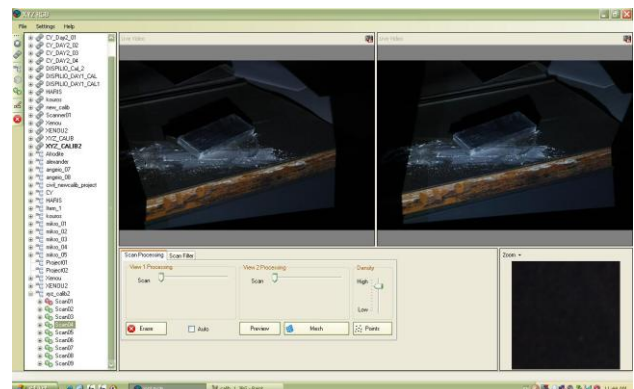

Figure 15: A sample data pair of one of the gauges

The formation of the meshes of both gauges was then enabled for the GSI software and the results are presented in Figure 16. The gauges were scanned a couple of times each from a slightly different position.
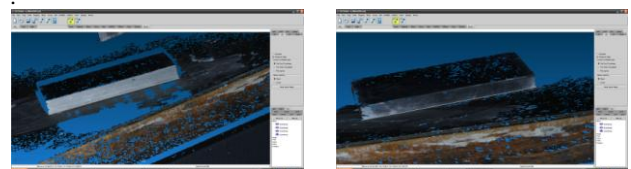

Figure 16: The meshes of the two gauges

The length of the two gauges was measured several times, each on the respective 3D mesh of two independent scans. The results of the various measurements are shown in Table 1. It is obvious that although the overall accuracy is within the manufacturer's specifications, the individual measurements present a deviation, which sometimes exceeds the claimed 50 microns.

	Gauge 80mm		Gauge 100mm	
	Length (mm)	**$L_i - L_m$** (mm)	**Length** (mm)	**$L_i - L_m$** (mm)
1	79,9401	-0,0091	100,0655	0,0312
2	79,9390	-0,0102	100,0384	0,0041
3	79,9597	0,0105	100,0063	-0,0280
4	79,9511	0,0018	100,0369	0,0026
5	79,9562	0,0070	100,0244	-0,0099
	L_m=**79,9492**	rms=**0,0094**	L_m=**100,0343**	rms=**0,0217**
	Length	$L_i - L_m$	Length	$L_i - L_m$
1	79,9380	-0,0110	100,0742	0,0411
2	79,9360	-0,0131	100,0346	0,0015
3	79,9624	0,0133	100,0052	-0,0279
4	79,9534	0,0043	100,0300	-0,0031
5	79,9557	0,0066	100,0216	-0,0116
	L_m=**79,9491**	rms=**0,0115**	L_m=**100,0331**	rms=**0,0256**

Table 1: Measurements of the industrial gauges

4.3 Implementation Examples

The experience gained form various projects, in which the SL2 scanner system was used adds to its positive image. A successful implementation of SL2 was for the three dimensional digitization of the Dispilio vases (Valanis et al., 2009a). The mostly clay vases with some painted decorations presented an excellent object for 3D digitization. Another implementation was for digitizing various artifacts in the Archaeological Museum of Lefkosia and the Byzantine Museum of the Archbishop Makarios' Foundation in Cyprus. Object material was the key role for the success or the failure of the task. The mosaics of Kanakaria presented difficulties only where the tessarae were gold plated. Jewelry and golden grails were almost impossible to reflect light. Icons on the other hand, although paint was sometimes very reflecting, could be oriented in such a way to avoid direct reflections to the system. Sculptures made of marble, e.g. Aphrodite, were a really difficult object.

Another successful application was the implementation of the scanner for the virtual restoration of the Zalongon moument. It was only with the SL2 system that the 1:5 models of the replacement of the damaged heads was possible to be scanned and digitally added to the 1:1 three dimensional object, in order to produce 1:1 drawings for the restoration of the monument (Valanis et al., 2009b; Ioannidis et al., 2010).
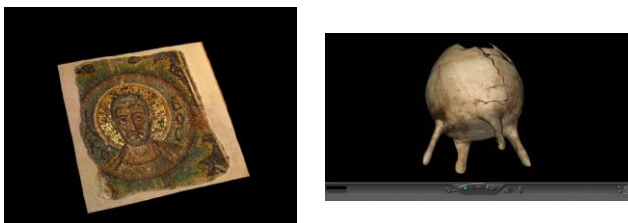

Figure 17: Examples of 3D renderings of a mosaic from Kanakaria (Cyprus) and a vase from Dispilio (Greece)

5. CONCLUDING REMARKS

With the tests performed, it has beeen shown that the performance of the XYZRGB ® SL2 system is within its accuracy limits as set out by the manufacturers. However accuracy measurements are greatly affected by the position of the nodes of the mesh, whose density can only vaguely be determined by the user. Repeated measurements cannot be performed reliably, as they are biased by the mesh composition. The tests performed concern only the specific object distance, which was approximately 1m. However, this tends to be the range for which the system is required to perform at its best. As for colour, the performance of the system is dependent on the quality of the images taken, as is the case in all similar situations. Colour information is directly attached to the built meshes.

Very crucial for the scanner results was the surface of the object. For artefacts that are shiny or light absorbent the performance is rather poor and satisfactory results are not easy to obtain. Although the manufacturer recommends the use of polarizing filters, they do not make the difference in most of the case.

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7. ACKNOWLEDGEMENTS