DESIGN OF A PROTOTYPE® FOR PHOTOGRAMMETRY FROM A SINGLE IMAGE, BASED ON SPECULAR REFLECTION

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Technical Commission II

KEY WORDS: Single image, mirror, specular reflection, photogrammetry.

ABSTRACT:

The present work presents a low-cost prototype® designed for the photogrammetric survey of small objects, from a single photographic shot. To do this, it relies on the different perspectives of the object presented by a series of mirrors conveniently placed in front of the camera lens. The set of specular reflections projected on the sensor of our camera simulates the same effect as having taken these photographs from the equivalent points for each mirror. A small script for dividing the image taken by the sensor into as many images as there are reflections, allows us to work with the usual shape from stereo photogrammetry procedure.
This prototype® allows, not only to photograph small inert objects more quickly but also enables the photogrammetric survey of small living beings, such as an insect, that cannot remain still during the traditional photographic image taking.

1. STATE OF THE ART

The first who exposed the possibility of using mirrors for stereo photography of an object (without the need to move the camera or the object) was Mikhail (1968), who noted that multiple perspectives can be captured without moving the camera using mirrors. Kratky (1975) used them for modelling limbs of the human body, and Murata et al. (1985) developed a theoretical model of photogrammetry with a mirror for the measurement of the coordinates of a moving body. Mitsumoto et al. (1992) used mirrors to symmetrically align the direct and mirror images to find correspondences between them using a vanishing point. The use of multiple mirrors made it possible to see the hidden parts of an object, thus enabling a full 3D reconstruction of an object.
Tokarczyk et al. (2000) developed a photogrammetry system that used mirrors, and that was applied in the field of medicine and the railway industry. Ebrahim et al. (2001) developed a mathematical model for the use of a mirror to measure objects, but only in one plane (stereo-photogrammetry). Hu et al. (2005) developed an algorithm for the orientation of the mirrors and the distance between them and the camera. Akay et al. (2014) described the problem of using multiple RGB-D cameras, proposing the use of mirrors to introduce these cameras virtually into the system.
Thomaidis (2014) investigated in his doctoral thesis whether and how a mirror changed the reference frame of an external observer. A “Mirror Transformation” algorithm was developed to generate a common point cloud by transforming the points from the plane of a front surface mirror into the point cloud. Finally, Kontogianni et al. (2018) used this “Mirror Transformation” algorithm for 3D reconstruction in two case studies, i.e., Image Based Modelling and Range Based Modelling.

2. METHODOLOGY AND DATA ACQUISITION

Other previous jobs go through the configuration of work scenarios with as many cameras as shots you want to take; generally, on the order of 18 to 24, but there are examples of up to 94 (Marshmallow Laser Feast, 2014). This procedure requires a scenario with the necessary structure for the situation of so many cameras, with the consequent high cost of digitization.
The works listed in the previous chapter present the theoretical framework that supports the use of mirrors in data collection for photogrammetry. In general, they propose and simulate simple cases, applicable to stereo-photogrammetry, but they endorse its use so that the mirror images can be used directly as working images as if they were independent photographic shots.
In this paper, we present the results of our research, in which we have tested with different numbers of mirrors, different arrangements of these concerning the object and the camera, and different distances between the camera and the object, based on the results of some of the aforementioned texts. As well as the best way to illuminate the entire scene.

2.1 Theoretical framework

The fundamental equation of the plane mirror is:

$$s' = -s \tag{1}$$

where s= the distances of the object to the origin O, located at the optical vertex.
s'= the distances of the reflected image to the origin O.
.

The equation states that s and s' are equal but opposite in sign; hence the real and virtual objects are equal but symmetrical. The same would happen if, instead of the object, we spoke of the real and the virtual camera (fig. 1). This scheme enables us to use flat mirrors to replace possible virtual cameras since their reflected image would be the same as those virtual cameras would take, but symmetrical.

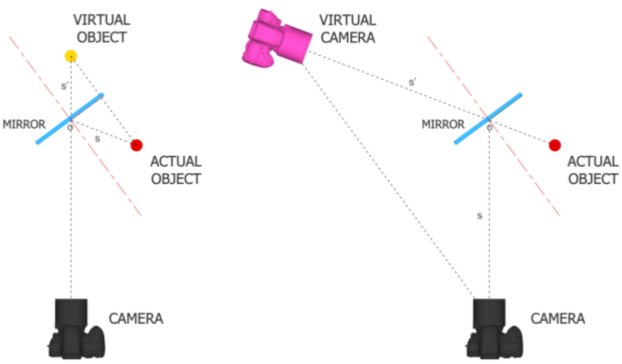

Figure 1. Ray diagram for reflection: left, of the object in its virtual position; right, of the camera in its virtual position.

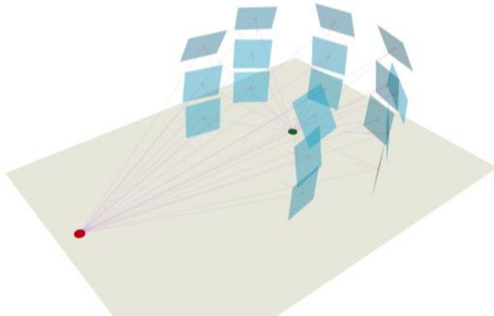

Figure 2. 3d model of mirror placement and simulation of visual rays and optical axes.

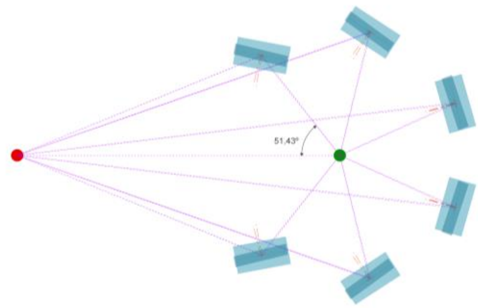

Figure 3. Plan view of the placement of the mirrors in front of the camera and the object.

The camera is positioned at a suitable distance so that, in combination with the focal length, a shot can be taken that makes the most of the sensor surface (fig. 4). The result is an image, therefore, made up of 18 reflections and one direct image (fig. 5); which allows the freezing of time for all the images, in the same light and static conditions.

Figure 4. Homemade construction of a photographic set of 18 mirrors.

Figure 5. Image from the camera viewfinder.

Material for data acquisition

The premise with which we start for the realization of this prototype® is that it be low cost. Thus, for the acquisition of the images we have worked with:

- Canon Camera 1000D, with 10.1 Mpx APS-C sensor CMOS of 22x14 mm (3888 x 2592 px). The size of the camera sensor is fundamental for a test like this since it has to be divided into 19 parts, in addition to wasting the surfaces that do not provide relevant information. So, the resulting size of each virtual shot has a resolution of 520x520 px; which is equivalent to a virtual camera of 0.27 Mpx (which is very little).
- Lighting set consists of a 220V AC SMD5050 60 LED/m neutral white LED strip; on a geodesic wooden support cut for this purpose, to provide continuous and uniform lighting throughout the piece, without shadows.
- 18 normal flat mirrors. These mirrors have a layer of glass on the front and a metallic reflective surface on the back. They are mirrors that, due to their nature, are not the most suitable because, in addition to the reflection of the reflective layer, they also produce the refraction of the glass that protects it. They are mirrors that therefore project an undesirable ghost image (Wikipedia, 2022).

2.2 Data acquisition

In successive trials, different scenarios were tested: with two mirrors, four, six, twelve and eighteen mirrors; having obtained the best results with this last set. And in various arrangements: vertical, horizontal, central, etc. The mirrors have been placed according to an initial arrangement calculated by a virtual 3d simulation, although their position has been slightly corrected in situ. This aims to simulate the route that is usually made around the object, photographing it at different heights; where, on the other hand, the shots don't need to be strictly at the same distance from the object, as is already known. The number of eighteen mirrors responds to the intrinsic need for photogrammetry that there is sufficient overlap between the photographic shots. And also, that the arrangement between the mirrors keeps a necessary angle (51,43º) so we can virtually go around the object (fig. 2 and 3).

The resulting image projected on the camera sensor is divided, by programming a *Photoshop* automation, into 18+1 individual images (fig. 6). This automatism, in addition, inverts the images reflected by the mirrors because, as we have already seen, they are symmetrical.

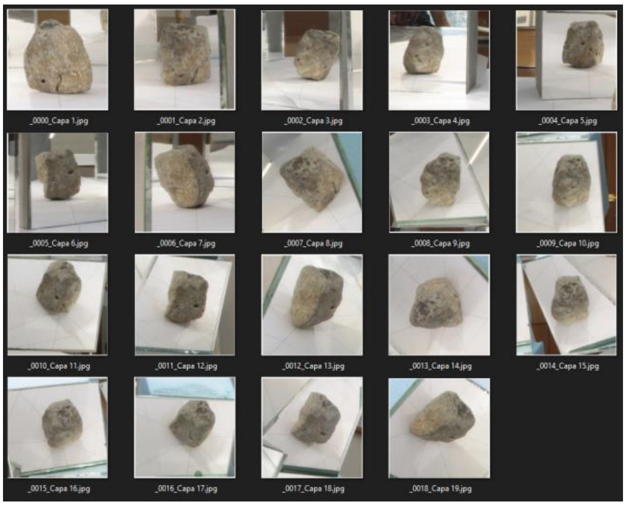

Figure 6. The 18+1 images cropped by the *Adobe Photoshop* automation.

2.3 3d modelling

The process of data collection through photogrammetry, for the documentation of the object, has been carried out in two ways:

a) with the “traditional method” to generate the control model. Three rings of converging photographs have been made at different heights, leaving the object fixed and rotating the camera on it. To achieve a complete model, this process has been carried out in two phases, first making the stone resting on one of its bases and, later, turning it over and resting it on the opposite base. A total of 54 photographs have been taken (fig. 7).
b) with the “mirror prototype®” to generate the study model. Now a single photograph has been taken in which the object and its reflection can be seen in each of the 18 arranged mirrors, thus achieving 19 different points of view of the object in a single image. This image is processed, as we have already seen, in the Photoshop photo editing program to decompose it into 19 individual images of identical dimensions (fig. 8).

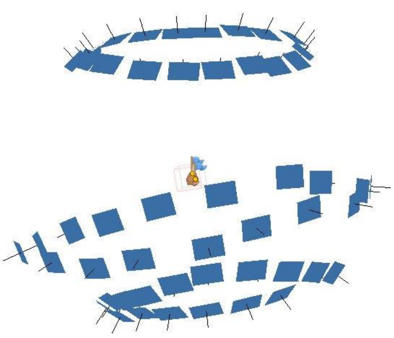

Figure 7. Alignment and position of the cameras by a) method.

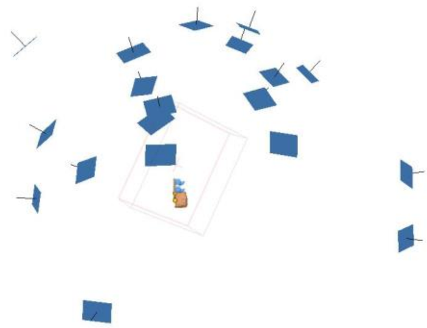

Figure 8. Alignment and position of the cameras by b) method.

In both cases, the photographs have been processed with the *Agisoft Metashape* software to obtain a solid model with texture. To do this, the usual workflow described below has been followed.

Once the photographs have been imported, the scattered cloud that defines the geometry of the object has been calculated using the orientation of the cameras, finding their positions in space. The next step has been the calculation of the triangle mesh using depth maps, which yields a higher quality mesh definition. The quality of these models has been made in “Ultra High” quality to achieve the best definition on the surfaces. The traditional model a) is made up of 874,092 faces and the model of the prototype® of mirrors b) 27,265 faces (fig. 9).

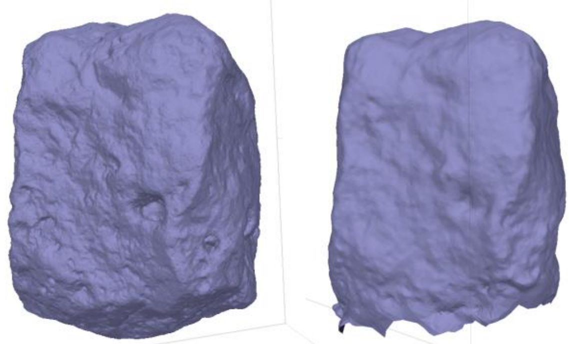

Figure 9. Level of detail of the triangle mesh obtained by photogrammetry with *Agisoft Metashape*: left, mesh obtained by a) method, with 874,092 faces; and right, mesh obtained by b) method, with 27,265 faces.

Finally, the texture has been calculated in 4K, although this is not necessary for the geometric comparison process of the 3d models. To give an identical scale to the two models, two markers have been introduced at identifiable points on the surface of both models and a measurement value has been introduced between them (3 cm). The last step is the export of the two 3d models to compare them geometrically and thus be able to check the quality and precision of the model obtained a) with the prototype® of mirrors b).

Already in this first phase of processing the photographs, comparing both systems, it is observed that the result is quite good geometrically, since in the mirror prototype® b) the complete geometry of the object has been obtained. This is poorer than that obtained by method a) due to the combination of three causes:

- fewer photos (19 vs. 54)
- dimensions of the camera sensor (10.1 Mpx) that, when cropped by 19, generates virtual cameras of 0.27 Mpx

- mirrors with the rear reflective layer, which generates refraction of the protective glass, in addition to the reflection of the reflective layer itself.

2.4 Model Comparison

To know metrically how precise the geometry is, the comparison of both meshes is made with the *CloudCompare* software, by calculating the deviation between the two surfaces and taking the model a) as a reference.
Both models are scaled and placed in the same position. They are then aligned, for which the study model b) is moved and rotated until it coincides with the position of the control model a). A finer adjustment is made through the action "Finely registers already (roughly) aligned entities (clouds or months)". Several parameters are indicated, and which model is the reference a) and which one is adapted b). The two models are then compared by choosing the "Cloud/Mesh Dist" option. The reference model is a) and the one being compared is b). This comparison is displayed visually by a color scale on the object (fig. 10) and a C2M histogram (fig. 11).

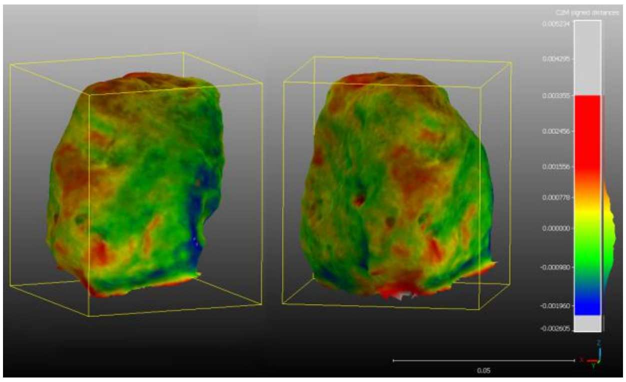

Figure 10. Graduated color ruler indicating the deviations obtained between the distances of the meshes of both models. The figure shows two different positions of model b) in which these colored deviations are seen.

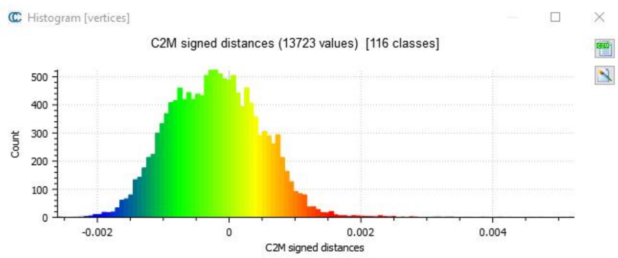

Figure 11. C2M Histogram that compares both surfaces into 116 classes.

The result shows that both surfaces fit quite well. The histogram shows 13,723 comparison values classified into 116 classes. A quick count shows that half of these (59) have errors of less than ±2 mm. But in addition, they are the ones that gather the most values; that is, most of the mesh surface. The rest of the classes (57) barely have representation on the surface of the mesh, so their errors are not very significant and are mainly reduced to the support area of the object and the lower part, not modelled by the b) method.

3. EXPERIENCE WITH A LIVING MODEL: THE SNAIL

The first test with a living being (a snail) yields promising results, although it is true that there are still variables to optimize. In addition to those already mentioned in chapter 3.4, we must add the need for more efficient lighting that allows shorter exposures in photography.
As a sample, we bring the model of a snail of which it will be difficult to check deviations from its original geometry, as it is in constant movement and change (fig. 12).

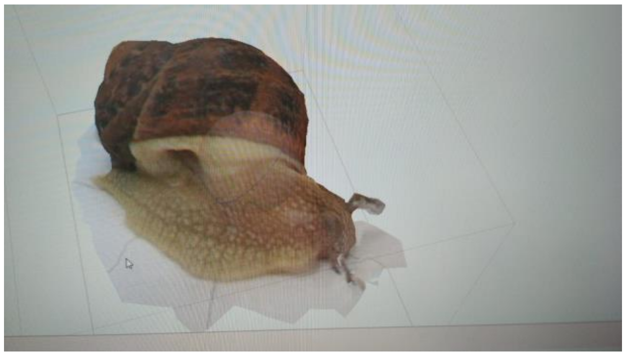

Figure 12. Snail tiled model textured.

4. CURRENT AND FUTURE JOBS

The present work proposes a procedure that still needs to be improved. In fact, in the phase we are in, we are working on two necessary lines. The first is to improve the design of the prototype® so that it can be easily manipulated and moved; even be built by 3d printing anywhere. This improvement involves: testing with more mirrors, defining the pieces for the 3d construction of the prototype®, optimizing the layout of the mirrors, incorporating flat mirrors with a reflective front surface, optimizing the stage lighting and the possibility of incorporating cameras, with a full-frame sensor, which provide higher resolution images.
The second is to carefully evaluate the accuracy of the models obtained by this procedure.

5. CONCLUSIONS

In this work, we present a prototype® for the photogrammetry of small objects, through specular reflection and a single photographic shot. This prototype® has been tested in practice with very promising results. We are currently continuing to run tests to estimate the accuracy of the resulting models and to see how they can be improved. It can be concluded that it is possible to obtain a 3d model of the objects from a single image with the help of several mirrors reflecting the object in that single image.
This work procedure has a potential that we estimate is very high. The realization of a three-dimensional virtual catalogue, for example, of a natural science museum, for a collection of insects, is an obvious application; even more so by not stating that the insects must be dead.

https://doi.org/10.5194/isprs-archives-XLVIII-2-W1-2022-1-2022

ACKNOWLEDGEMENTS

The authors are grateful to Alfonso Román, the technician at the model laboratory of the Valladolid School of Architecture, for his precious support in preparing the experimental set-up.

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