REVOLUTIONIZING PHOTOGRAMMETRY: USING MIRRORS IN SINGLE-IMAGE PHOTOGRAMMETRY

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ABSTRACT:

The present work introduces a new low-cost prototype® designed for photogrammetric surveys of small objects, using a single photographic shot. The prototype® utilizes the different perspectives of the object presented by a series of mirrors strategically placed in the camera sensor. The set of specular reflections projected on our camera sensor simulates the same effect as taking pictures from equivalent points of each mirror.
The v1 prototype® was presented at the 7th International Workshop "Low-Cost 3D Sensors, Algorithms, Applications" in Würzburg on December 15-16, 2022. It consists of a set of eighteen common mirrors conveniently placed around the object to be digitized, making its reflections converge towards the camera lens. The v2 prototype® presented here is an evolution of the previous one, which replaces the common mirrors with precision ones that have a metallic reflective surface on the front. This modification eliminates the double image formed by the reflective layer and the protective glass.
These prototypes® allow for faster surveys of small inert objects (such as small cultural heritage artefacts like sculptures, engravings, rings, coins, etc.) as well as photogrammetric surveys of small living beings, such as insects, which cannot remain still during traditional photography.

1. INTRODUCTION

This paper presents a low-cost prototype® designed for the photogrammetric survey of small (living, or not) things, from a single photographic shot, using 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 captured by our camera sensor simulates the same effect as taking these pictures from the equivalent points of each mirror.
In this paper, we compare the prototypes® v1 and v2 in which the size and quality of mirrors have been improved: from a rear to a front metallic reflective surface.
These prototypes® allow for quicker surveying of small inanimate objects, but also enable photogrammetric surveys of small living beings, such as insects, that cannot remain still during traditional photographic picture-taking.

2. STATE OF THE ART

2.1 The use of mirrors in photogrammetry

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.
In his doctoral thesis, Thomaidis (2014) investigated whether and how a mirror could alter the reference frame of an external observer. To achieve this, he developed a "Mirror Transformation" algorithm that could 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) later used this "Mirror Transformation" algorithm for 3D reconstruction, in two case studies, i.e., Image Based Modelling and Range Based Modelling.
The previous works provide the theoretical basis for using mirrors in data collection for photogrammetry. Generally, they propose simple scenarios that are only applicable to stereo-photogrammetry. However, they endorse using mirror images directly as working images, as if they were independent photographic shots.

2.2 Photogrammetry for the living things survey

Photogrammetry has been used in biology and ecology to study living beings, including animals, plants, and fungi. It allows for precise and replicable measurements of different aspects of organisms, making it a valuable tool in these fields.

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Examples of photogrammetry used for creating accurate 3D models of small objects include Nguyen et al.'s 2013 method, which utilized high-resolution images and a specialized acquisition device to create 3D models of entomological specimens. In 2014, an improved prototype was presented for acquiring compact, high-quality 3D models of insects using photogrammetry. In 2021, Plum and Labonte presented scAnt, an open-source platform for creating 3D digital models of arthropods and small objects using Extended Depth of Field images and an automatic masking routine. This platform is accessible and affordable, making it useful for machine learning-driven behavioural studies and digitization efforts in natural history collections.

All the methods mentioned so far require the condition that the living beings are deceased. However, Mungee and Athreya (2020) described a rapid, simple, accurate, and inexpensive method for conducting morphometric studies on thousands of free-ranging insects attracted to light screens using images taken without collecting a specimen or even restricting the individual in any way.

2.3 Previous works: prototype® v1 and its evolution to v2

The proposed procedure aims to replicate the process of capturing images of an object from multiple angles in a traditional photographic set. This is achieved by using multiple cameras to capture images simultaneously, which envelop the object in a virtual sphere. Earlier works have used between 18 to 24 cameras to achieve this, with some examples using up to 94 cameras (Marshmallow Laser Feast, 2014).

The v1 prototype® was introduced at the 7th International Workshop "Low-Cost 3D Sensors, Algorithms, Applications", at Würzburg, 15-16 December 2022 (Álvaro-Tordesillas *et al.* 2022). It comprises eighteen mirrors strategically placed around the object to be digitized, directing their reflections towards the camera lens. Consequently, a single photograph captures eighteen views of the object, emulating the conventional practice of surrounding the object for photography.

The v2 prototype we present here is an improved version of the previous one. It incorporates precision mirrors with a metallic reflective surface on the front to eliminate the double image formed by the reflective layer and the protective glass in the earlier version.

3. METHODOLOGY AND DATA ACQUISITION

We evaluated several factors for the design and construction of the v1 prototype®, including the number of mirrors, their arrangement relative to the object and camera, and the distance between the camera and the object. We also looked into the most effective way to illuminate the scene. Based on our findings, we decided that a set of mirrors positioned around the object at angles of 51,43º would be ideal, as shown in Figures 1 and 2. This configuration was used for the v2 prototype as well.

3.1 Theoretical framework

The fundamental equation of the plane mirror is:

$$s' = -s \qquad (1)$$

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.

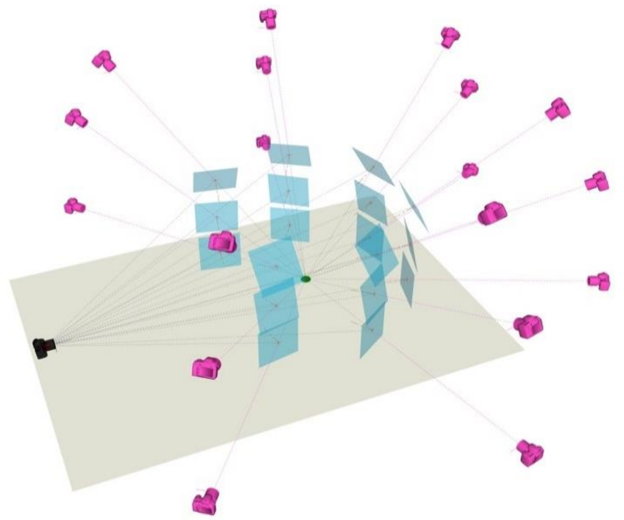

Figure 1. 3d model of 18 mirror placement and simulation of 18 virtual cameras (pink) position.

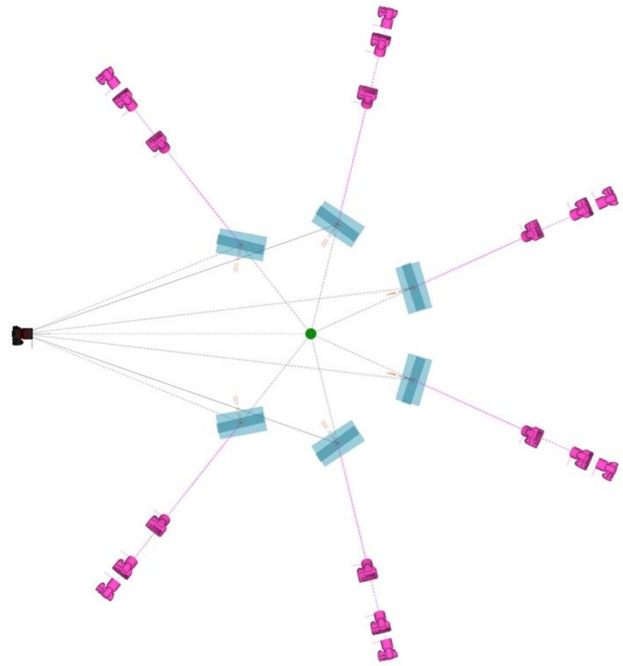

Figure 2. Plan view of the placement of the 18 mirrors in front of the real camera (black), the object (green) and the virtual cameras (pink).

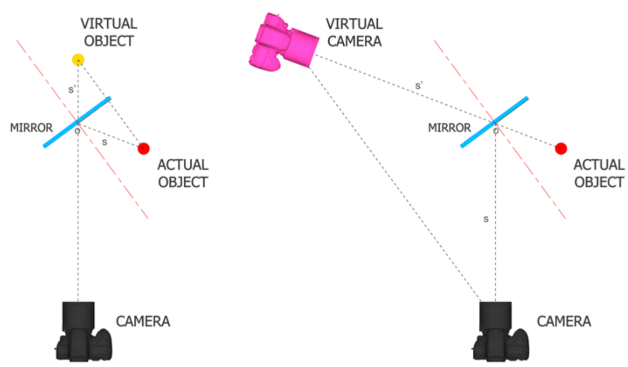

Figure 3. Ray diagram for reflection: left, of the object in its virtual position; right, of the camera in its virtual position.

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. 3). 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.

3.2 Material for data acquisition

The premise with which we designed the v1 prototype® was that it must be low-cost. Thus, for the acquisition of the images we worked with:

- Canon Camera 1000D, with 10.1 Mpx, APS-C sensor CMOS of 22x14 mm (3888 x 2592 px).
- Lighting set consists of a 220V AC SMD5050 60 LED/m neutral white LED strip.
- 18 normal flat mirrors. These mirrors have a layer of glass on the front and a metallic reflective surface on the back.

The v2 prototype involves replacing the mirrors with precision reflective ones that have a metallic reflective surface on the front. Its specific characteristics are: flat 70 mm 2,75 inches. Minor axis length: D=70 mm; tolerance: ±0,5; Surface Accuracy (λ):1/4; Coating: Aluminum + protective film.

3.3 Data acquisition

As we explained earlier, we have tested different configurations of the scene before settling on 18 mirrors arranged in columns of six by three, forming angles of 51.43º between each column, around the object to be digitized. Mirrors were placed according to an initial arrangement calculated by a virtual 3D simulation, slightly corrected in situ, to simulate a walk-around of the object. The camera is positioned at a suitable distance to take advantage of the sensor surface with a focal length of 35mm. The resulting image is made up of 18 reflections, allowing for consistent light and static conditions.

Figure 4. Prototype set (v2). View from the camera.

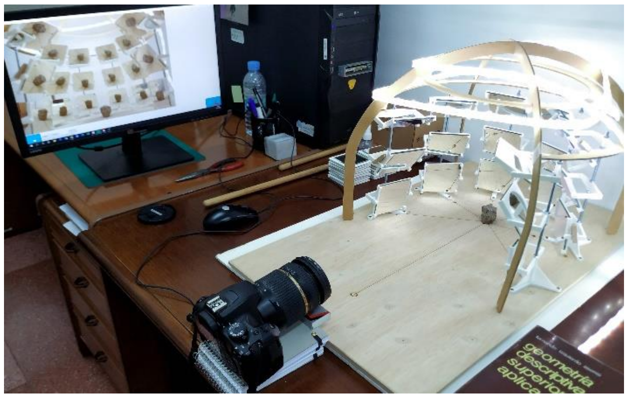

Figure 5. Prototype set (v2). General view.

Figure 6. Image (v2) from the camera viewfinder.

The resulting image projected onto the camera sensor is automatically divided into 18 individual images using *Adobe Photoshop* automation (fig. 7 and 8). This process also flips the images reflected by the mirrors.

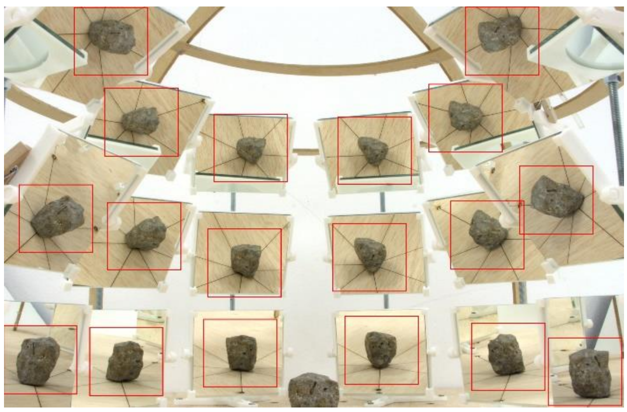

Figure 7. Selecting, cropping, and flipping the 18 reflection images (v2) from the camera viewfinder.

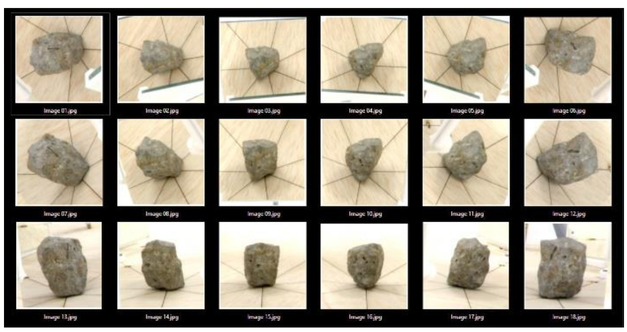

Figure 8. The 18 resulting images.

3.4 3d modelling

The photogrammetric process has been conducted in two ways:

a) The "traditional method" was used to generate the Control Model, which involved taking three rings of converging photographs at different heights while keeping the object fixed and rotating the camera around it. A total of 54 photographs were taken, as shown in Figure 9.
b) The "mirror prototype®" to generate the Study Model. Now a single photograph has been taken and processed as we have said. We obtain 18 images of 18 different points of view of the object (fig. 10). By this method we have obtained two models: b1) with the mirrors of the v1 prototype®; and b2) with the mirrors of the v2 prototype.

The photographs have been processed with the Agisoft Metashape software to obtain a solid model with texture.

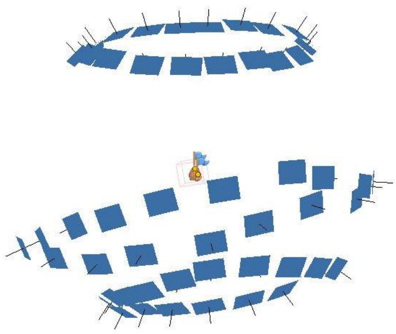

Figure 9. Alignment and position of the cameras by a) method.

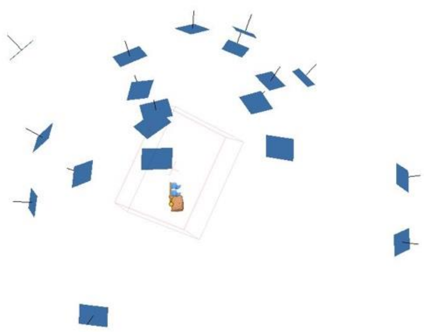

Figure 10. Alignment and position of the cameras by b) methods.

The software recognises all the virtual cameras and were oriented and located in the 3d virtual space. The scattered cloud that defines the geometry of the object has been calculated using this orientation of the cameras. It is necessary to highlight how the complete geometry of the object has been obtained, despite the low resolution of the images; that is saying a lot.
Next, it is calculated 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 triangles (fig. 11). The mirror model b1) 27,265 triangles, and b2) 42633 triangles (fig. 12); that means that b2) model has much more definition.
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 models, two markers have been introduced at identifiable points on the surface of the models and a measurement value has been introduced between them (3 cm).

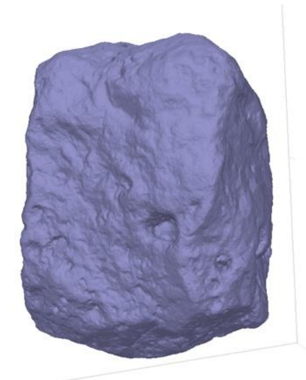

Figure 11. Mesh obtained by a) method, with 874,092 triangles.

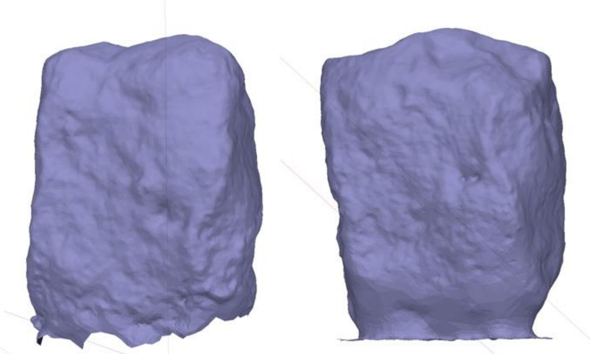

Figure 12. Left, mesh obtained by b1) method, with 27,265 triangles; and right, b2) method, with 42,633 triangles. They are rotated 360 degrees relative to each other.

The last step is the export of the 3d models to compare them geometrically and thus be able to check the quality and precision of the model obtained a) with the mirror prototypes® b1) and b2).

3.5 Conditions before the Comparison and Results

b2) model should be poorer than a) but better than b1) model due to the combination of two causes:

- a) model is made up of 54 images, while the b) models are made up of 19 and 18 images
- a) model images are 10 Mpx size, while the cropped images are 0,27 Mpx size.
- And b1) model images are made up of rear reflective layer mirrors, while b2) model images are made up of front reflective layer mirrors.

4. MODEL COMPARISON

The meshes are compared with the Cloud Compare software, by calculating the deviation between the two surfaces and taking the model a) as a reference, to know how precise the geometry is.
All the models are scaled and placed in the same position. They are then aligned, moving, and rotating the study models b1) and b2) until they coincide 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 ones are adapted b1) and b2). The three models are compared in pairs (ab1 and ab2) by choosing the "Cloud/Mesh Dist" option. The reference model is always the a) one.
These comparisons are displayed visually by a colour scale on the object (fig. 13 and 15) and a C2M histogram (fig. 14 and 16).

The result shows that both pairs of surfaces fit quite well. In a first view, the b1) method model looks poorer than the b2) one. Which is, obviously, due to the mirrors.
The histogram (ab1) shows 13,723 comparison values classified into 116 classes. A quick view shows that most of the values (82,8%) have errors of less than ±1 mm; this is most of the mesh surface.

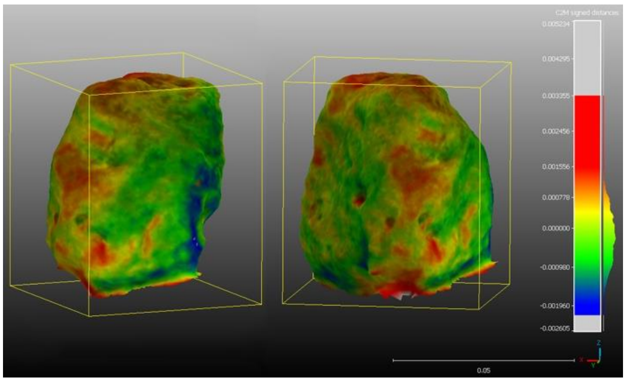

Figure 13. Graduated colour ruler indicating the deviations obtained between the distances of the meshes of both models a) and b1). The figure shows two different positions of model b1) in which these coloured deviations are seen.

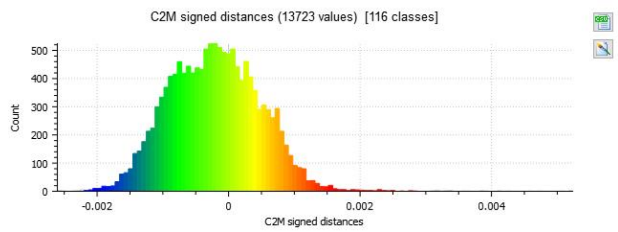

Figure 14. C2M Histogram (ab1) that compares both surfaces a) and b1) into 116 classes.

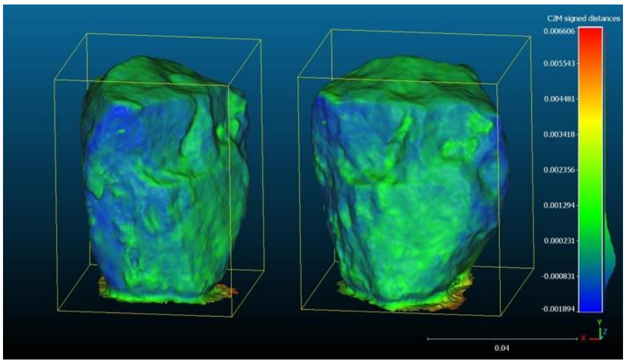

Figure 15. Graduated colour ruler indicating the deviations obtained between the distances of the meshes of both models a) and b2). The figure shows two different positions of model b2) in which these coloured deviations are seen.

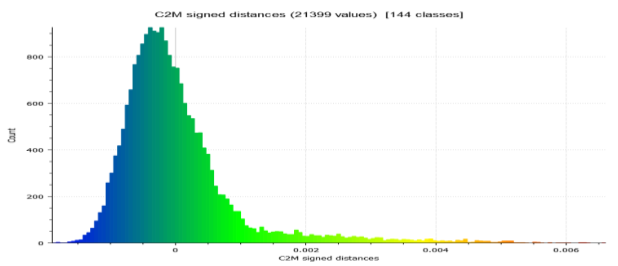

Figure 16. C2M Histogram (ab2) that compares both surfaces a) and b2) into 144 classes.

The rest of the values (17,2%) barely have representation on the surface of the mesh, so their errors are not significant and are mainly reduced to the support area of the object and the lower part, not modelled by the b1) method.
The histogram (ab2) shows 21,399 comparison values classified into 144 classes. We can appreciate how the surface fits much better to the control model, finding a deviation of ±1 mm, in 90% of its surface; this is almost its entire surface. The worst values (4,2%) barely have representation on the surface of the mesh and are also reduced to the support area of the object.

	<1mm	1mm-2mm	>2,00mm
a) – b1)	82,8%	16,6%	0,6%
a) – b2)	90,0%	5,8%	4,2%

Table 1. Percentage of surface error in mm between model pairs ab1 and ab2.

5. EXPERIENCE WITH A LIVING MODEL

All the tests we have done so far have used small stones and chalk pieces since we are still in the prototype stage. Once it functions perfectly and the model results are adequate, we will try it with some cultural heritage objects.
But we also wanted to evaluate its potential for taking pictures of objects that are moving. So, we tried with a living, moving snail, with promising results (fig. 17); and in the future, we will try with other small insects: beetles, bees, bed bugs, ants… In these tests, we realised that we also need to improve in more efficient lighting that allows for shorter exposure times.

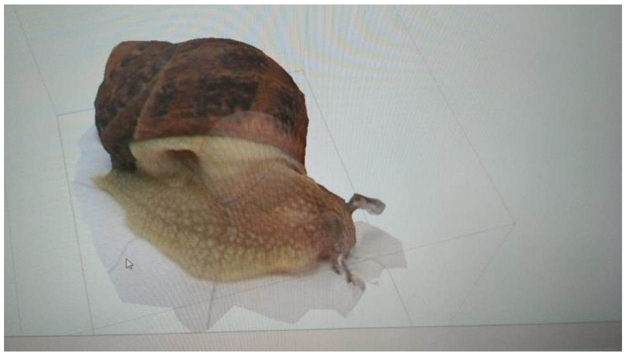

Figure 17. Snail-tiled model textured.

6. CURRENT AND FUTURE JOBS

The present work proposes a procedure that still needs to be improved. Today we are investigating the best way to position the mirrors to use most of the sensor surface, and not waste pixels. In this way, we are currently working on developing a custom Rhino/Grasshopper script that will allow us to position the mirrors efficiently and accurately, according to the specifications of each camera we use. This script will streamline our workflow and reduce the likelihood of errors or inconsistencies in our mirror placement, ultimately resulting in more precise and reliable photogrammetric models.
Thanks to this Grasshopper analysis, one possible outcome is that by reducing the number of mirrors to 17, we can obtain a greater surface area of the sensor utilized (as shown in Fig. 18).
We are also performing a set with a better new 8K Full Frame camera sensor (Canon EOS R5 C), around 45 Mpx (8192x5464).
We have also designed the pieces of the v2 prototype, so it could be easily 3d printed and constructed anywhere.

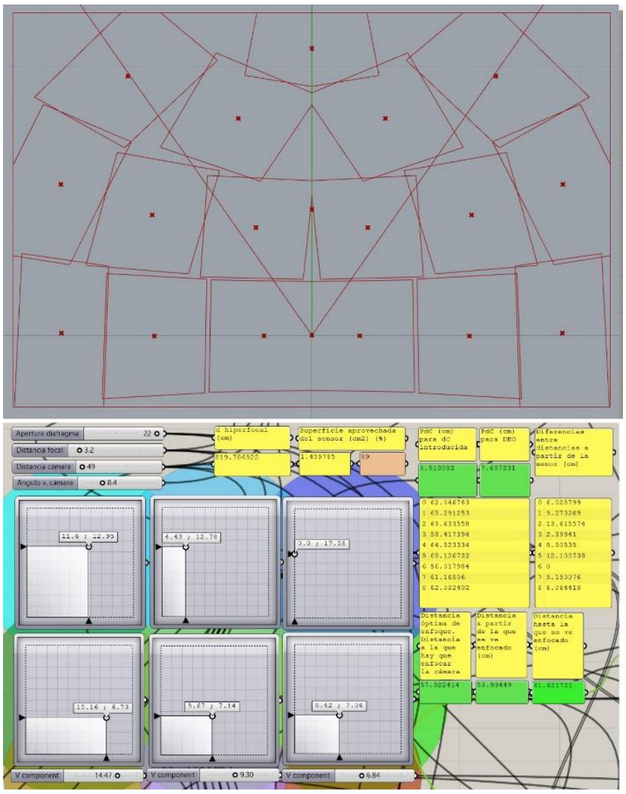

Figure 18. Rhino/Grasshopper script to improve the utilization of the sensor surface.

7. CONCLUSIONS

In this work, we present an optimized version (v2) of a prototype® designed for the photogrammetry of small (living) objects using specular reflection and a single photographic shot. The v2 prototype has been evaluated with very promising results. We are currently running further tests to estimate the accuracy of the resulting models and identify areas for improvement. Our findings demonstrate that it is possible to generate a 3d model of an object from a single image with the aid of several mirrors reflecting the object in a single picture.
We believe that our approach has high potential and could be applied to accelerate the digitization process of small cultural heritage objects and create a three-dimensional virtual catalogue of a natural science museum collection of insects; just to cite a couple of examples.

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