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Prototyping the complex biological form of the beetle Deltochilum Lobipes via 2D geometric morphometrics landmarks and descriptive geometry for 3D printing

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ABSTRACT

In this paper, we present research carried out in the Morphometric Laboratory, Institute of Ecology, in Xalapa, Veracruz, México, which consisted of creating a new method that links geometric morphometrics techniques and descriptive geometry. In our new method a collection of five photographs was used to tag each morphological point called "Landmarks" that defines the numerical values of the coordinates "x" and "y" in a Cartesian space to generate through the coordinates "x," "y" and "z" the geometry of the biological form of a beetle, across surfaces, meshes and solids. In this research we worked with the beetle Deltochilum Lobipes that belong to the Scarabaeidae family. We made two prototypes in 3D printed, from the 2D coordinates of morphological points which were obtained through the tpsDig2 program. This research documents evidence that supports the hypothesis of our project: "the quantitative descriptor of shape and size in 2D, contribute in the modeling of complex geometric structures in 3D".

1. Introduction

Insects (class: Insecta) are arthropoda (Phylum: Arthropoda). Arthropods are invertebrates that are the most diverse phylum of the animal kingdom. These animals have the body covered by an exoskeleton known as cuticle and formed by a series of linear segments with articulated parts.

Beetles are insects belonging to the order Coleoptera. The word "coleoptera" is from the Greek $\kappa o \lambda \epsilon ó \varsigma$, *koleos*, meaning "sheath"; and $\pi \tau \epsilon \rho ó \nu$, *pteron*, meaning "wing," thus "sheathed wing," because most beetles have two pairs of wings, the front pair, the "elytra," being hardened and thickened into a shell like protection for the rear pair and the beetle's abdomen.

Beetle Deltochilum Lobipes, belong to the kingdom *Animalia*, phylum *Arthropoda*, class *Insecta*, order *Coleoptera*, family *Scarabaeidae*, tribe *Canthonini*, gender *Deltochilum* and subgenus *Hybdomidium* (Fig. 1 (a)).

It is among the 160 and 1000 meters above the level of the sea and mainly associated with dry forest, their main activities are nocturnal, has an opaque black color and its length varies between 15 and 25 mm.

In the beetle Deltochilum Lobipes, there are three body regions: head, thorax and abdomen which can be separated. There are two pairs of wings, the hind wings and the elytra, and six legs which they are divided into two parts.

When we separate the beetle we found fifteen parties (Fig. 1 (b)), of each party five photographs were taken from above, front, back, right side and left side, for simulate in a graphic editor (in this case we use Photoshop CS6) the orthogonal projection.

For the orthogonal projection, the camera, was placed on a support (Fig. 2(a)), we designed and 3D printed: a holder (Fig. 2(b)) with a height of 10 cm, to place the beetle parts since they are very small, most parts range in size from 6 to 15 mm long, except the two wings measuring 30 mm long, and a palette (Fig. 2(c)) 18 mm wide to mark the distance between the camera and the parts, to maintain the same scale in all photos.

In the technique of geometric morphometric was used the tpsDig2 program (Rohlf 2008 [1]) to find, through the photographs, the coordinates values "x "and "y" of the morphological points called "landmarks" [3] the criteria for choosing landmarks in light of both biological and mathematical considerations, focusing on general criteria and principles.
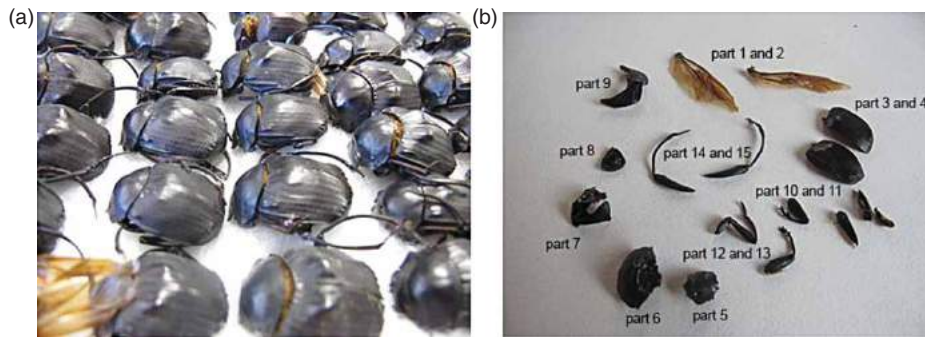
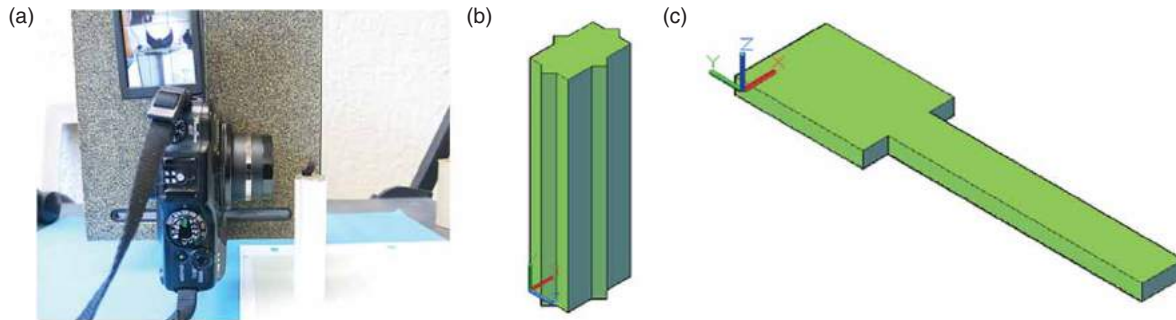**Figure 1.** (a) Beetle Deltochilum Lobipes and (b) Beetle parts.

Figure 2. (a) Camera on a support, (b) Holder and (c) Palette.

With the numerical values of the coordinates "x" and "y" of the "landmarks", the numerical values of the coordinates "x," "y" and "z" were found, and they were traced, in the AutoCAD program, the contour, the position of the protrusions, the change of the curvatures, the intersection of the planes, the change of planes, the position of junction points and flat shapes of the parts of the beetle, ending with the modeling and 3D printing of the geometric forms.

We can said that the objectives in this study were achieved: (1) describe the shape and size of the biological parts from beetle through the geometric morphometrics techniques, and (2) build three-dimensional prototypes using the resources and elements of descriptive geometry.

This paper is organized as follows: in section 2 we explain the arrangement of the orthogonal projection and tagged points, in Section 3, we explain the numerical values of the coordinates "x" and "y" of the "landmarks". In Section 4 we explain the three-dimensional modeling. Section 5 presents the assembly of the two models. Section 6 presents the 3D printing of the two prototypes. Section 7 presents the results. Section 8 presents the contributions and finally Section 9 presents the conclusions. We want to mention that all the figures presented in this paper are original and created by the authors at the Morphometric Laboratory, Institute of Ecology, in Xalapa, Veracruz, México.

2. Arrangement of the orthogonal projection and tagged points

We perform the arrangement of the orthogonal projection of a cube (Fig. 3(a)) and of a complete beetle (Fig. 3(b)) to assess the accuracy of the scale through five, and three photographs respectively. The results were satisfactory so we proceeded to work with the elytra.

The elytra is placed on the holder (Fig. 4), are taken five photographs from the front, back, above, left side, and right side using the palette as a scantling to mark the distance between the camera and the object.

In the graphics editor (Photoshop CS6) four lines at 45° angle are traced to simulate the orthogonal projection that indicate the change of planes. The five photos are placed in each of the planes and checked first of all that all the photographs are at the same scale.

Through the intersection of the guides were tagged with colored dots (Fig. 5) the four points of the lines at 45° angle and the projections of the points in space in at least three of the planes of the orthogonal projection, i.e. in the vertical, horizontal and lateral and/or in the horizontal, posterior and lateral planes.

These points are the cross-referenced that define the contour, the position of the protrusions, the change of the curvatures, the intersection of the planes, the change of planes, the position of junction points and flat shapes of the elytra.
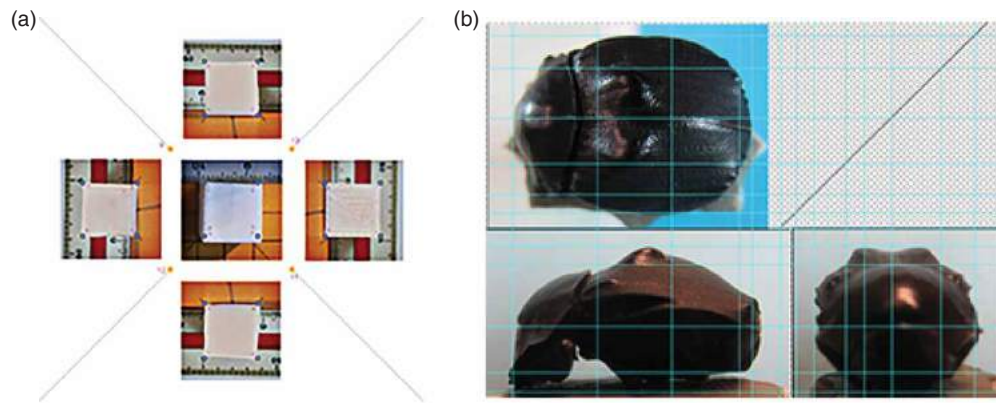
Figure 3. Assessment of the scale of the photographs in the orthogonal projection: (a) Cube and (b) Beetle.

Figure 4. The elytra on the holder.

We tagged 91 points in the top view, 43 points in the front view, 55 points in the back view, 52 points in the right side view and 50 points in the left side view.

Table 1. Tagged points in the eleven parts.

Part	Points	Part	Points	Part	Points
1	291	5	284	9	59
2	200	6	203	10	127
3	100	7	136	11	90
4	115	8	124		

In each of the eleven parts of the beetle, as some are repeated, the following points were tagged (Tab. 1). And then was saved as JPG file.

3. Numerical values of the "landmarks"

The JPG file is opened in the tpsDig2 program, the tagged points are marked in the same order on

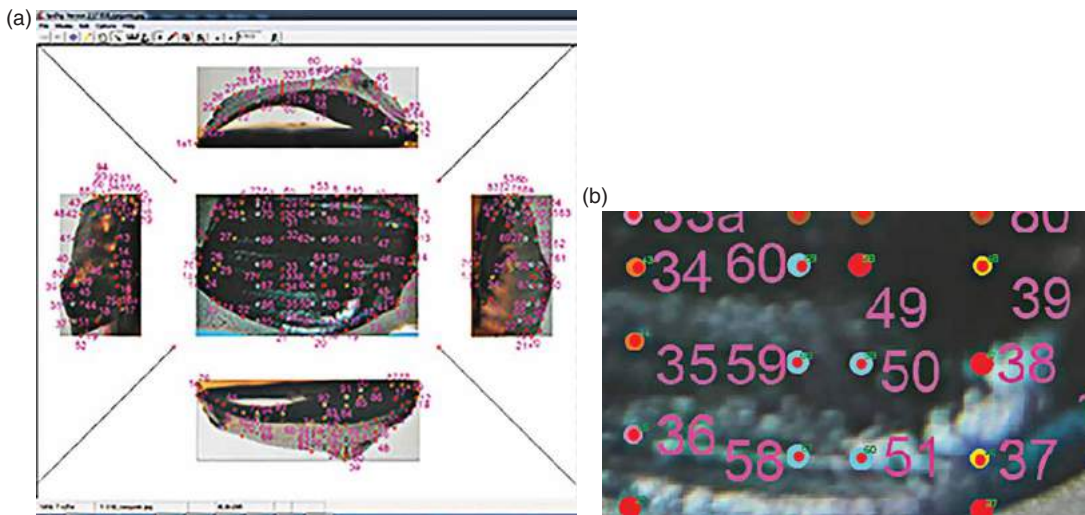**Figure 5.** Tagged points in the orthogonal projection.

Figure 6. Registration points in tpsDig2 program: (a) All planes and (b) Detail.

Table 2. Numerical values of the axes and numerical values for one curve of the elytra.

Axes	X	Y	Points	Top view X	Top view Y	Front and back view X	Front and back view Y	Right and left side view X	Right and left side view Y
1	550	1281	19	1239	680	1240	1636	193	680
2	1611	1284	37	1238	721	1237	1702	128	720
3	1612	616	38	1240	790	1239	1728	103	789
4	548	616	39	1239	863	1238	1743	88	861
			40	1239	948	1240	196	130	949
			41	1238	1051	1240	211	141	1050
			42	1238	1152	1239	238	171	1151
			43	1237	1188	1240	251	182	1187
			8a	1239	1221	1237	301	228	1221

Table 3. Numerical values of the axes and one curve of the elytra.

Axis	X	Y	Points	Top view X	Top view Y	Front view X	Front view Z	Left view Z	Left view Y	Concatenation
1	550	1283	19	1239	682	1239	355	355	682	1239,682,355
2	1612	1283	37	1239	721	1239	421	421	721	1239,721,421
3	1612	616	38	1239	790	1239	446	446	790	1239,790,446
4	550	616	39	1239	861	1239	461	461	861	1239,861,461
			40	1239	949	1239	420	420	949	1239,949,420
			41	1239	1051	1239	407	407	1051	1239,1051,407
			42	1239	1132	1239	379	379	1132	1239,1153,379
			43	1239	1186	1239	367	367	1186	1239,1186,367
			8a	1239	1221	1239	323	323	1221	1239,1221,323

each of the planes, i.e. on each of the photographs (Fig. 6 (a)).

In Figure 6 (b) we can see that the red dots that are above of the color points are the marked points in the tpsDig2 program.

The program tpsDig2 creates a text file that contains the numerical values of the coordinates "x" and "y" of each of the points, considering the origin 0, 0 in the lower left side [2]. For simplicity, we illustrate the numeral values of the axis and solely the points of one of the curves of elytra in Tab. 2.

The numerical values of the coordinate "x" and "y" are adjusted between the same coordinates to the average value or value most repeated.

The numerical value of the coordinate "z" was found by subtracting, considering the highest numerical value, the numerical value of the coordinates "y" among the axes and the front and back views, and the numerical values of

the coordinate "x" among the axes and the left and right side views.

At the end, the three numerical values of the coordinates "x", "y" and "z" of each point (Tab. 3) are concatenated. All these concatenated numbers were saved from Excel in a CVS format.

4. Three-dimensional modeling

The numerical values of the concatenation are copied from the Excel file and are pasted into an AutoCAD file and automatically points are traced in space. In the same way the wire frame is traced automatically by means of a spline.
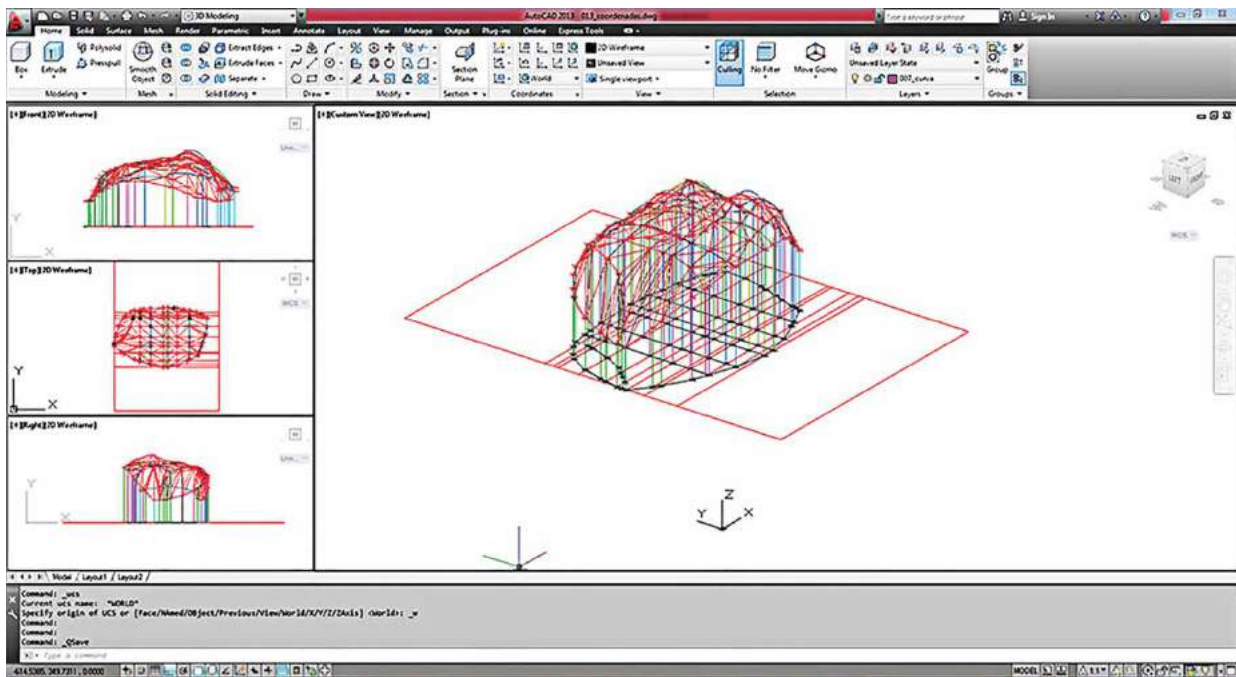
Figure 7. Shape of elytra via point and wireframe.
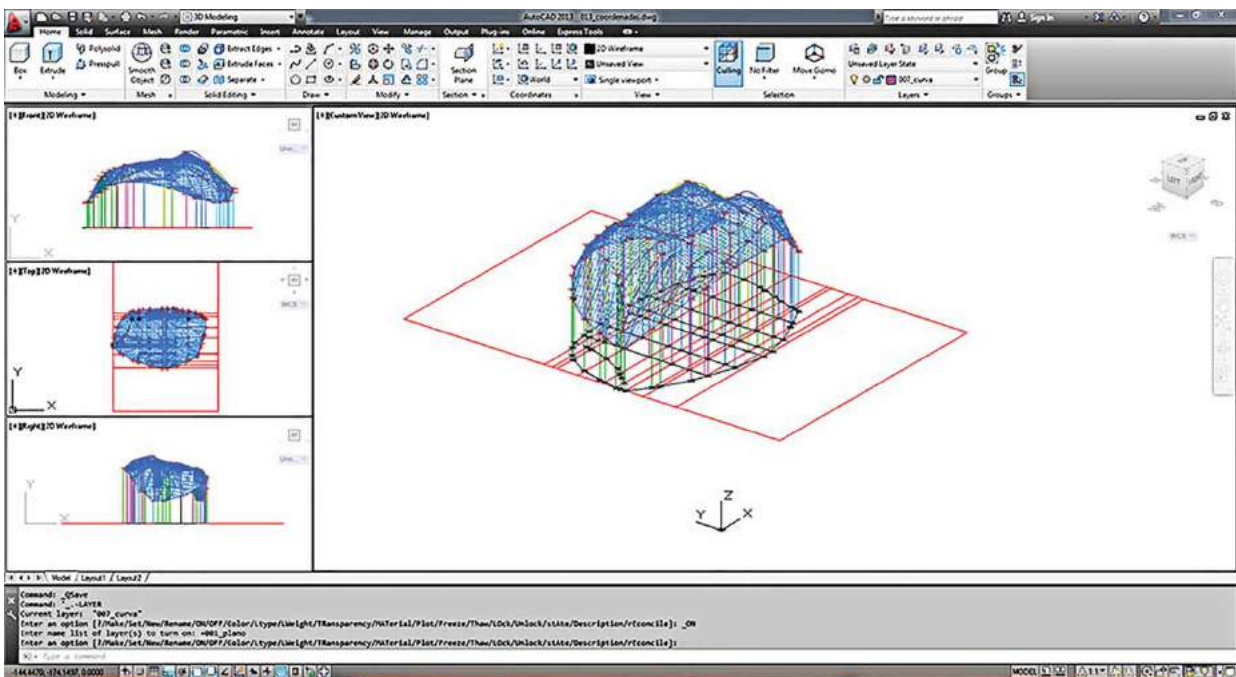
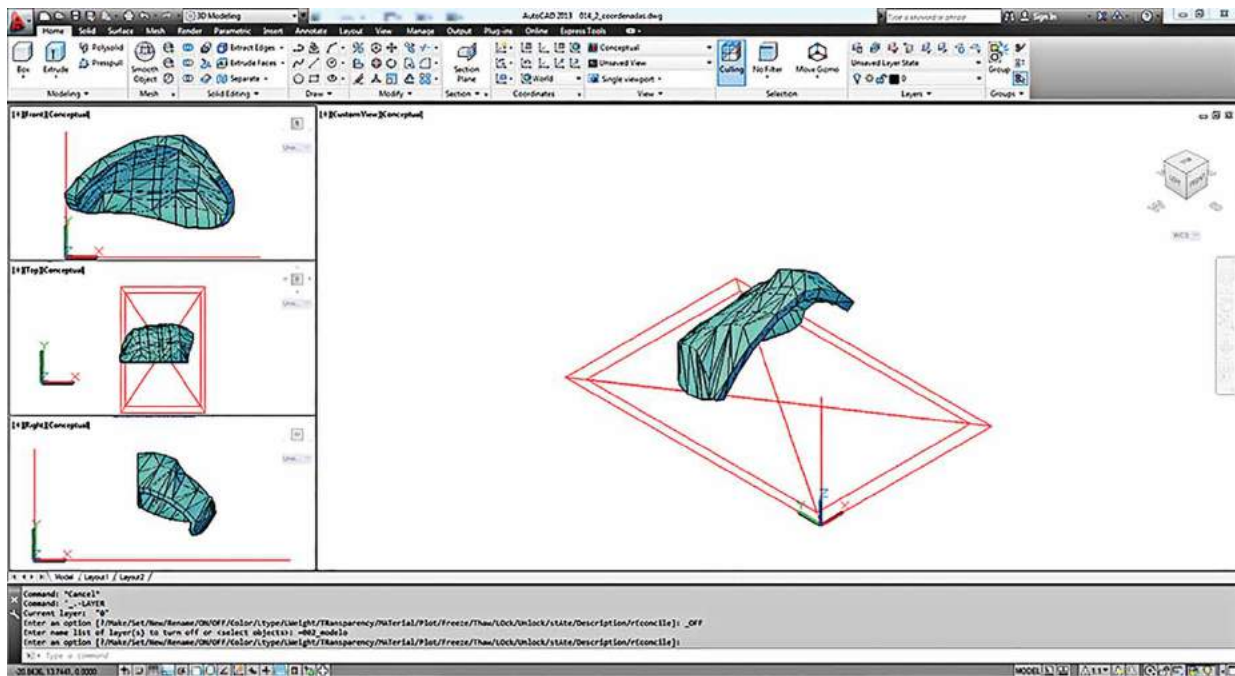**Figure 8.** Shape of elytra via triangulation.

Figure 9. Shape of elytra via surfaces.

The coordinates "x," "y" and "z" are the points in space defining the shape of elytra, and the coordinates "x" and "y" are the projections of the points in space on the horizontal plane in the orthogonal projection (Fig. 7).

The geometry of elytra is based on triangulation. So that, each rectangle of the mesh that formed is triangulated to define the position of each of the surfaces in space of the curved shape of elytra (Fig. 8).

From the union of surfaces is formed the solid. The surfaces are joined into a single entity, are duplicated, are scaled and placed at a distance of 4 mm to give the thickness of the elytra (Fig. 9).

3D printing was performed. The elytra was scaled to 60 mm long, considering the total size of the beetle and the print area of the 3D printer.

It is checked first of all, that all surfaces are bonded at the edges in order to create the solid model. The model it was exported as STL file. The STL file is opened in the MakerBot program, the x3g file is created and sent to the Makerbot Replicator 2 printer for printing.

It ends with the verification of the prototype with the original shape of elytra (Fig. 10).

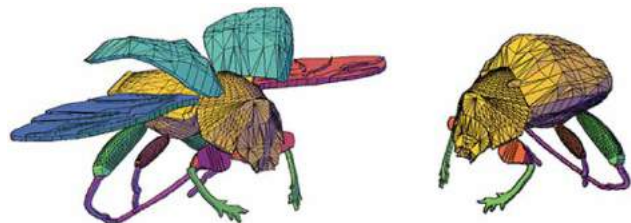**Figure 10.** Comparison of 3D prototype with the elytra shape.

Figure 11. Assembly of the two beetles modeled in AutoCAD.

5. Assembly of the two models

We do the assembly of the two models in the AutoCAD program (Fig. 11) to know how to connect each of the parts of the beetle before making 3D printing.

The models were cut longitudinally to analyze the assembly of each of the parts that were modeled (Fig. 12) in the AutoCAD program. With this cut we realized that it was necessary to add some parts to assemble printed models.
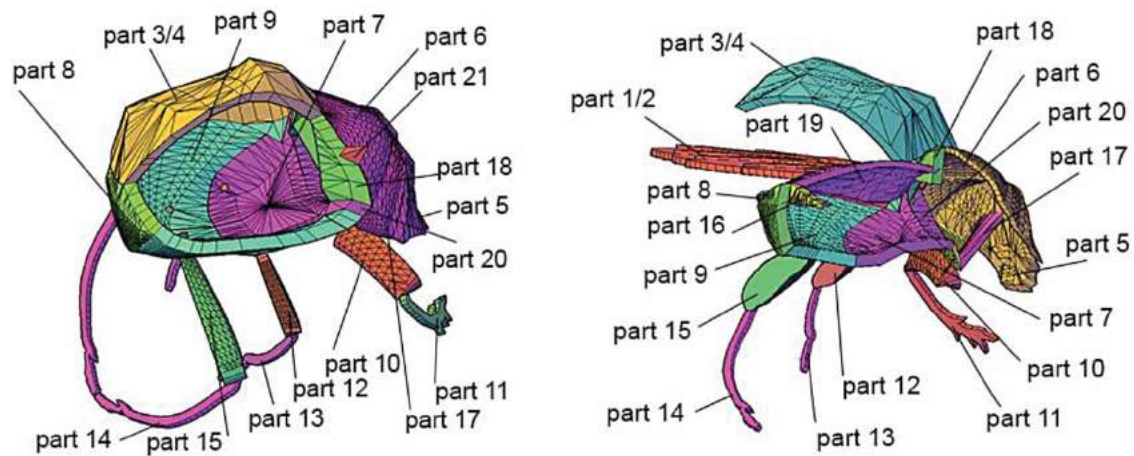
Figure 12. Longitudinally cut: (a) Wingless beetle and (b) Winged Beetle.
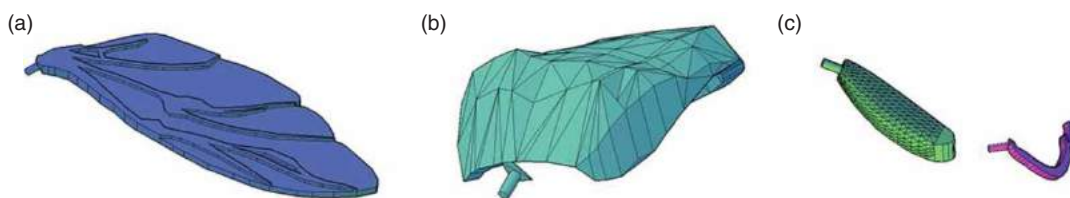

Figure 13. Pivots: (a) Wings, (b) Elytra and (c) Legs.

So, five parts were added: Part 18 was added to attach on top, the head with the body. Part 20, was added to attach on the bottom, the head with the body (Fig. 12 (a) and (b)).

Part 16 is added in the winged scarab to bind the abdomen (Part 19) with the body, and part 17 was added to attach the bottom of the head to the body (Fig. 12(b)).

To assemble the wings, elytra and legs in the body of the winged beetle, were added a pivot of 2.5 mm thick with a length of 5 mm (Fig. 13 (a), (b) and (c)). Finally, they were added in the model of the winged beetle, four brackets (Part 21 in Fig. 12), two for the elytra and two for the wings to be sustained because the parties are open.

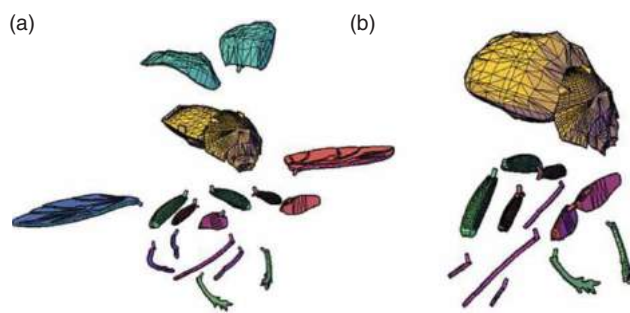The explosion of the two models (Fig. 14) shows how assemble the parts of the two beetle.
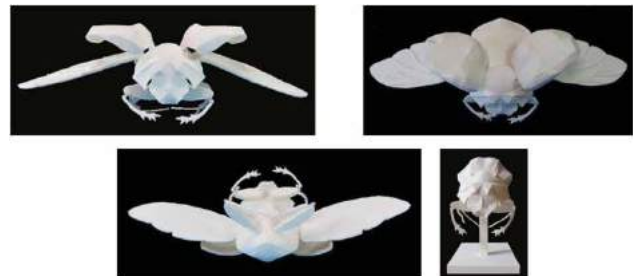
6. Prototypes

Figure 15. 3D printing of the two prototypes.

7. Results

The most common methods used to collect the data of three-dimensional objects or biological forms are the scanning and the digitizing.

In scanning of objects or organic forms, a line of laser passes over the surface of the organic forms and the information is recorded. The data of the surfaces are captured by a sensor through a camera that recorded the density or number of points in the space without touching the object.

Figure 14. Explosion: (a) Wingless beetle and (b) Winged Beetle.

Figure 16. Archaeological piece.

Figure 17. Feet, Parts 14 and 15.
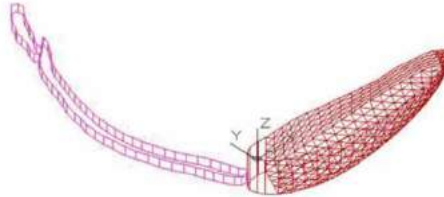
If we want to see the internal parts of biological forms, should be considered the use of CT Scanning that combines a series of images taken from different angles, where processes computer are used to create images cross sections or through cuts.

In digitizing, is used a pointer that passes over the object or organic forms to collect the information. The 3D laser digitizing are generally used in the automobile, aerospace and entertainment industry.

The literature tells us that to obtain good results in scanning and digitizing objects or biological forms should be considered: the brightness of the light, the reflection material and that objects do not move. Also should be considered that all points and surfaces found must be rectified before creating the mesh or solid.

In the project called Dimensional Scanning archaeological artifacts (Fig. 16) held at the National Institute of Anthropology and History (INAH) and the Center for Research in Mathematics (CIMAT) of the State of Guanajuato, Mexico, the procedure that was performed to scanning an archaeological piece is the following [4]: (1) The piece is placed on a pedestal at a certain distance from the scanner and the light is regulated to avoid reflections. (2) After obtaining the data from the first scan, manually the piece is rotated at intervals of 30° to capture the 360° of the same. (3) The part that is in contact with the pedestal and the top of the piece is scanned separately. (4) After completing the full scan of all the sections in which the piece was divided, all digital files are stored.

The researcher says that during the scanning process of this piece, found different complications inherent in the process and the capacity of the scanner to recognize objects whose edge is very thin because the laser is unable to record a proper amount of points. So they had to extend the area of captured and perform greater number of shots in the same sector of the piece from different angles, creating overlapping images. This made the registration of the different shots that will make up the final model becomes a little long and complicated, and requires more "cleansing" of the individual shots to avoid the possible redundant information.

Another problematic situation is the one that has to do with the lighting at the time of shooting, because when is changed the piece position to get a new image has a variation in the tone of the pigment.

With this example we can say that when it scanned or when it digitized an object or a biological form, what is being done is a faithful copy of them. With our new method, it was not created a faithful copy of the beetle, rather, what was done was geometrize the biological form of the beetle through the points of spatial correlation that were labeled in five photographs.

With these points were found the numerical values of the coordinates "x," "y" and "z" to trace the orthogonal projection of the curved shapes of each of the parts of the beetle, so we can see in the following figures as the feet of the beetle were built following the same procedure that was performed with the elytra (Figs 17, 18 and 19).

The methodology used in our new method for the study of the biological form of the beetle using geometric morphometric techniques and descriptive geometry allowed us to:

1. Identify the morphology of the beetle through the observation of each of the parts and movements of the insect.
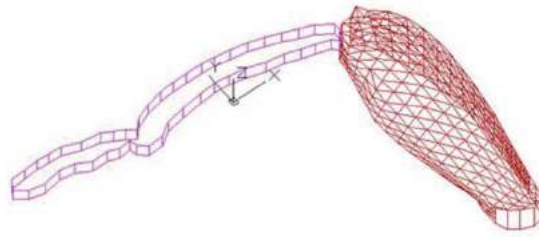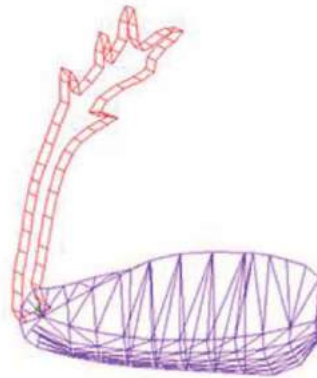
Figure 18. Feet, Parts 12 and 13.

Figure 19. Feet, Parts 10 and 11.

2. Perform the geometric development of each of the parts of the beetle in two and three dimensions.
3. Assemble the parts of the beetle.
4. Assess the prototypes versus biological form of the beetle.

With this new method, the results obtained in modeling the two prototypes are significant because first of all mathematically were corrected the numerical values of the coordinates "x" and "y" of each of the points in space. Were simplified the geometric shapes of the biological parts of the beetle, and were defined morphological characteristics of the Beetle parts.

8. Contributions

Techniques of geometric morphometrics and descriptive geometry, used their own procedure to find the shape and size of the biological form in a plane (2D) and in space (3D). In this research, we demonstrate, that quantitative description of the shape and size of the beetle that were registered through the geometric morphometric 2D "landmarks" contributed in the modeling of 3D prototype by means of descriptive geometry.

This research not only contributes in the scientific and educational field in the area of Biology, but also, contributes to the areas of Design, Architecture, Engineering and Robotics, because with this method, will be developed complex biological forms that can be used to perform structural and biomechanical studies.

9. Conclusions

To date, there has been no joint investigations between geometric morphometrics and descriptive geometry methods to find the points in a three-dimensional space to print 3D prototypes. The method described in this document will help researchers and students to create prototypes to study the morphological and geometrical properties of complex biological forms without 3D scanner or 3D digitizers.

Acknowledgements

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[4] http://remarq.ning.com/page/tecnicas-para-el-modelado-tridimensional-de-artefactos-arqueologicos