3D NASCA'S ZOOMORPHIC GEOGLYPHS RECONSTRUCTION

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ABSTRACT

This paper describes the 3D reconstruction of the Nasca plains zoomorphic geoglyphs. Smooth 3D models are obtained using aerial photographs as a starting point and adopting the symmetry and simplicity criteria which are normally used by human beings to infer three-dimensional information. In practice, the models are computed through the symmetrical elevation of silhouette skeletons of the Nasca plains drawings followed by an implicit function interpolation of the data provided by both the silhouette and the skeleton. The generated models are quite reasonable since the analytic nature of the interpolating function reproduce the soft aspect inherent to many organic shapes.

1. INTRODUCTION

The Nasca's geoglyphs constitute one of humanity's most important archaeological legacies, due mainly to their quantity, nature, dimensions, cultural continuity and the enigma that constitutes the purpose of their creation. World recognition of this fact came in 1994 when the UNESCO declared them World Heritage Site (UNESCO, 1994).

In order to avoid their gradual destruction (CNN, 2004; TWT, 2004), two international projects (Project Nasca/Palpa, 2004; Association Dr. M. Reiche, 2004) have been working in order to impel the preservation of these cultural legacies through the digitized documentation of the terrain together with the zoomorphs, fitomorphs and geometric figures that constitute the lines of the Nasca plains.

Contrary to these projects --that have as aim to build a digital terrain model and to constitute an exact and reliable data source for scientific research-- the aim of this work is to make 3D reconstructions of the objects represented by the zoomorphic geoglyphs of the Nasca plains. We concentrate on these objects because many of the geoglyphs represent, almost without ambiguity, the silhouette of quite well-known animals (e.g. "the condor", "the whale", "the spider"', "the monkey", etc.).

Considering each silhouette like the result of the 3D object projection on an arbitrary plane, the reconstruction can be seen as the inverse process of such a projection. Unfortunately, this process is mathematically undetermined since one silhouette could be produced by the projection of many different objects.

However, under some general assumptions it is possible to reach some simple and plausible results without any *a priori* knowledge about the geometry and topology of the objects. Our approach uses the ideas introduced by Igarashi et al. (Igarashi et al., 1999) in their work of interactive 3D free-form objects modeling, which consists on the elevation of a "skeleton", i.e., a curve generated from 2D polygonal information.

The techniques introduced by Igarashi are based on polygonal mesh representations, and as a result some models may be generated with unpleasant characteristics --wrinkled regions and with sharp and abrupt borders-- which are inappropriate for the problem at hand. The zoomorphs that we want to reconstruct, as well as many organic forms, are objects constituted mostly by soft surfaces. Implicit representations (Bajaj et al., 1997; Velho et al., 2002) are very well suited for this task, since they are able to model such surfaces in a very natural and elegant way.

This paper is organized as follows. Section 2 presents some relevant work related to the problem at hand. An overall description about Nasca culture and their geoglyphs is introduced in Section 3. Section 4 briefly introduces key concepts of the variational implicit surfaces. The involved algorithms on the reconstruction process are described in detail in Section 5. Finally, the results are presented in Section 6 and the conclusions in Section 7

2. RELATED WORK

It's important to highlight that this work does not propose or support any theory about the mystery of the the Nasca's lines creation. Basically, this work deals with the application of some techniques introduced in the literature for obtaining a 3D digital representation of objects represented by the Nasca's zoomorphic geoglyphs.

2.1 Nasca plains digitalization

Most of the Nasca's lines digitalization efforts are based on aerial photographs. Besides the photographs obtained by the Peruvian National Aero-photographic Service (SAN) between 1944 and 1970, many pictures were taken by photography fans or people interested in understanding the mystery of the lines existence.

Recently, two international projects (Project Nasca/Palpa, 2004; Association Dr. M. Reiche, 2004) started carrying out the 3D reconstruction and digitalization of the Nasca plains terrains. Basically, these projects aim to build a digital terrain model and a vectorial representation of the figures. This 3D model is reconstructed starting from high quality aerial photographs with modeling, analysis and visualization purposes. A second goal is to be able to constitute an exact and reliable data source for scientific research which will allow the evaluation of different theories about the origin and the reason for the creation of these geoglyphs.

2.2 Surface reconstruction

Many techniques to perform surface reconstruction have been proposed in the past. They can be categorized into simplicial, parametric and implicit approaches (Dinh, 2000).

Simplified approaches construct simplified elements from a collection of data points and then identify which simplicial complexes belong to the surface. In general, these techniques can only interpolate the data and are thus sensitive to any noise present in the data. Besides, they can present serious performance problems when faced with a large amount of data.

The parametric techniques describe the reconstructed surface by a parametric equation. Their main drawback is that, in order to represent a closed surface of arbitrary topology, multiple patches have be pieced together --a quite difficult problem, in general.

The implicit algebraic techniques tend to be elegant in constructing a single polynomial function to represent implicitly a complex surface. Usually, this function is defined as a combination of polynomials and its zero level set represents implicitly the reconstructed surface. Algebraic techniques present limitations to reconstruct surfaces of arbitrary topology, since simple and low order polynomials are insufficient to represent complex objects.

Techniques similar to the previous one, where the analytic function is not polynomial, can solve the problem of representing objects of arbitrary topology. Usually, the analytic function is defined as a lineal combination of non-polynomial basis functions. Savchenko et al. (Savchenko et al., 1995} and Turk (Turk and O'Brien, 1999b} introduced the use of radial basis functions for the implicit interpolation of the data points. Using this technique the problem of the softness and absence of data is elegantly resolved.

3. THE NASCA'S GEOGLYPHS

The inhabitants of the Nasca culture --between 400 B.C. and 550 D.C.-- made a great number of lines on the desertic surface of a region situated 450 km to the south of Lima, Peru, covering a total extension of approximately about 350 km^2 and raising 598 m from the level of the sea (Menchola, 1990).

Hundreds of straight lines (many of them parallel, some in zig-zag and others intersecting), big trapezes, spirals, triangles and drawings of giant animals are distributed in a chaotic way on the desert.

The surface of the area is composed by a layer of small stones of a dark reddish color caused by the oxidation. This covers another layer of stones of a clear yellowish color. The lines were created by removing the top stones following a layout that previously had pointed out with stakes united by cords. The removed stones were accumulated in small barrows that are still conserved. In that way, the gigantic lines and figures appear as clear lines on a dark bottom (Arrieta, 2004; Menchola, 1990).

If one keeps in mind that the ``designers'' could never observe their work, which can only appreciated from the air or partially from some hills, the perfection of the result is really attractive.

The weather took care of the conservation labor: the Nasca desert is one of the driest places in the world, with an average of a half hour of precipitations every two years. This way, the geoglyphs have always been prevented from being erased by the vegetation and torrential rains (Arrieta, 2004).

The well-known geoglyphs describe figures of animals, plants and geometric objects (Menchola, 2004) for a detailed classification of these geoglyphs). Some of the most famous ones are (Figure 1):

- The monkey: Famous geoglyph with approximately 135 m. It shows an animal with only nine fingers and a tail in spiral form.
- The spider: With 46 m. of length, it is located among a net of straight lines and is part of the edge of an enormous trapeze.
- The hummingbird: It is another of the most famous geoglyphs due to its harmonious proportions. The distance between the tips of its two wings is 66 m.
- The lizard: It measures 188 meters long. Their back legs were erased with the construction of the Panamerican South Roadway that divided the figure in two parts.

Many theories try to explain the meaning and purpose of these geoglyphs. Among the most serious we may distinguish five different categories (Aveni, 1990): (1) Astronomy and calendars. (2) Geometry and artistic expression. (3) Agriculture and irrigation. (4) Transport, movement and communication; including walks and dances. (5) Ceremonial practices. In spite of this, conclusive and satisfactory results have not been presented that explain the origin and the meaning of these geoglyphs (Reindel et al, 1999).

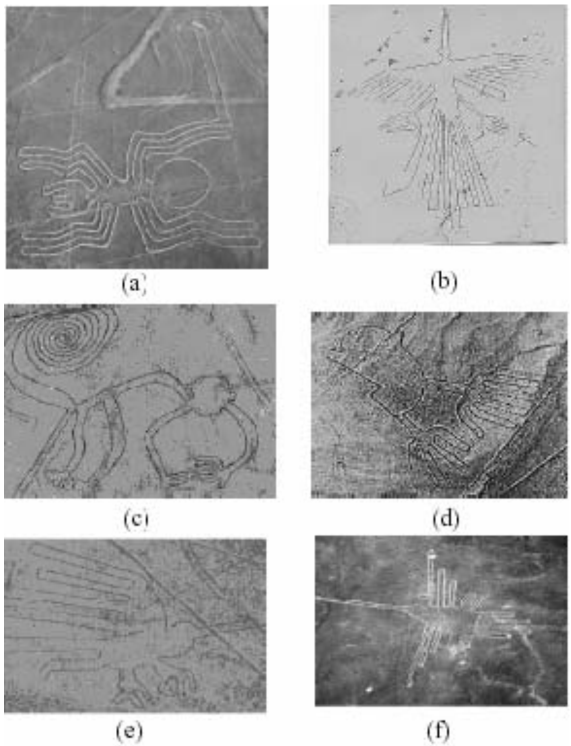

Figure 1. Photographs of some of the best-known Nasca zoomorphic geoglyphs. (a) "The spider". (b) "The condor". (c) "The monkey". (d) "The hands". (e) and (f) "The hummingbird"

4. VARIATIONAL IMPLICIT SURFACES

Although a thorough discussion of the math of implicit object modeling is outside the scope of this paper, for the sake of completeness, we try to lay down a few key concepts below. The interested reader is referred to the excellent introduction to the subject in (Turk and O'Brien, 1999a).

The term "`Variational Surface" refers to the zero-set of a RBF-based implicit function (i.e., the points where the function yields zero). Such functions are used in the context of scattered data interpolation. This is a problem where, given a set of n distinct constraint points $\{c1, c2, \ldots, cn\}$, $c \in R^3$ and a set of n function values $\{v1, v2, \ldots, vn\}$, it is sought a smooth function $f: \Re^3\ \Re \rightarrow$ such that $f(ci) = vi$, for $i = 1 \ldots n$. The smoothness criteria usually involve some "deformation" energy that must be minimized. This entails the solution of a linear system with n equations. We use a standard LU-decomposition algorithm for this task.

A variational surface can be modeled simply by choosing an adequate set of constraint points and associated values. The most used approach requires the placement of $n/2$ points with value equal to zero --these are known as *boundary constraint points*. Another set of $n/2$ points are obtained by displacing each boundary point by a small amount along the direction of the estimated surface normal at that point. These points -known as *normal constraint points*-- are associated with a small positive constant w.

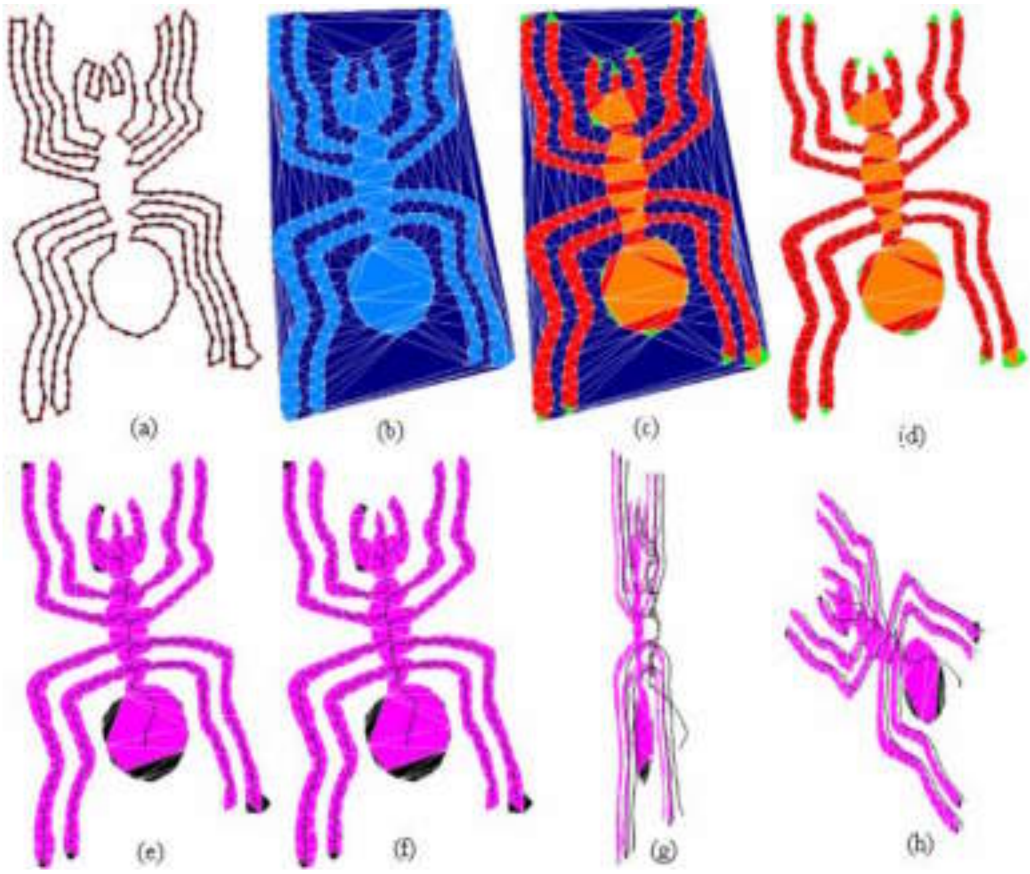

Figure 2. Generation and elevation of the skeleton of P. (a) Initial polygon. (b) Constrained Delaunay Triangulation. (c) Triangles classification. (d) Cordal axis computation. (e) Irrelevant triangles identification. (f) Calculation and smoothing of the skeleton. (g) and (h) Skeleton elevation.

Any standard method for visualizing implicit objects can be used to render variational surfaces (Bajaj et al., 1997; Velho et al., 2002). In most cases, a polygonization scheme is employed and the resulting set of polygons is rendered using standard graphics hardware.

5. 3D RECONSTRUCTION

This section describes the algorithms used in the 3D reconstruction of the geoglyphs. Images are presented that illustrate the results obtained in each stage of the reconstruction process. Such images correspond to the reconstruction of the geoglyph known as "the spider". Basically, the reconstruction process is performed in three stages:(1) constraint points generation, (2) RBF-based implicit interpolation and (3) visualization of the zero iso-surface.

The first stage receives as input an aerial photograph of some zoomorph figure. We extract the geometric information of the figure boundary and we represent it by means of a polygon *P*. Subsequently, the skeleton of *P* is determined and we proceed to carry out its elevation. The points of the elevated skeleton together with the vertices of the *P* will provide the necessary constraint points set for the next stage.

The interpolation stage receives as input a set of constraint points --- called *boundary constraint points*. From these, a new set of points is generated (called *normal constraint points*), which will determine the orientation of the surface. Subsequently, these points are inserted inside an interpolation process that will generate an analytic function $f: \Re^3 \to \Re$, where the zero level set of *f* represents the surface of the reconstructed object.

The last stage builds a polygonal approximation of the surface represented implicitly by the function *f* with visualization purposes. This approach is conceived through the construction of a mesh of triangles, this process is known as poligonization.

5.1 Constraint points generation

- Border detection. The geometric information of the figure silhouette is obtained product the their border detection. This was done using a manual process. Internally, the border information is represented by a simple polygon *P* which is stored using a double-linked list. Each list node stores information of one vertex of *P*. The vertices of *P* are resampled in order to obtain a polygon with uniform size edges and to delete duplicate vertices (Figure 2(a)).
- 2D Triangulation. The edges of *P* are inserted in a constrained Delaunay triangulation called *T* (Figure 2(b)). The algorithm used is based on Vigo's proposal (Vigo, 1997).
- Triangle classification. Each triangle of *T* is classified in one of the four groups (Figura 2(c)). Terminal{Ti}: triangles with two edges adjacent to *P*. Boundary{Bi}: triangles with one edge adjacent to *P*. Junction{Ji}: triangles without edges adjacent to *P*. External{Ei}: triangles positioned outside *P*.
- Cordal axis computation. The cordal axis *CA* is composed by the segments that join the middle point of the interior edges of the triangles Bi (Figure 2(d)). *CA* is

represented by a list of lists of nodes. Each node stores the middle point of the interior edges of the boundary triangles.

- Irrelevant triangles identification. For each branch of *CA* and starting out from a terminal triangle we proceed to the identification of irrelevant triangles, i.e., triangles that are contained on the circle whose diameter is equal to the length of the last visited edge (Figure 2(d)).
- Skeleton computation. The skeleton *E* of *P* is constituted by all vertex of *CA*, except those whose edges belong to irrelevant triangles (Figure 2(e)). The disconnected branches of *CA* are joined to *E* by joining the middle points of each junction triangle with the triangle circumcenter. The information associated with *E* is represented in a data structure similar to that used for the cordal axis.
- Skeleton smoothing. Due to some vertices of *E* appearing positioned more closer to one side or another of initial polygon, the skeleton may assume the appearance of a jagged object. In order to alleviate this problem, the skeleton edges are submitted to a smoothing process that rectifies the position of some of their vertices in an attempt to remove abrupt changes along the branches of the skeleton (see Figure 2(f)). The algorithm used is the one proposed by Taubin (Taubin, 1995}.
- Skeleton elevation. All skeleton vertices are elevated to a height that is proportional to their distance to *P* (see Figures 2(g) and 2(h)). The elevated skeleton is symmetrically duplicated on the other if the plane of polygon *P*. In other words, assuming that the vertices of *P* and *E* are positioned on plane z=0, then for each point (xi, yi, zi) of the elevated skeleton a new point is created at (xi, yi, -zi). We will refer to the skeleton having positive z coordinates as the *front skeleton* and to the skeleton having negative z coordinates as the *back skeleton*.

5.2 RBF-based interpolation

This process begins with specification of the constraint points that will constitute the input data for the construction of an RBF-based implicit function *f*, such that the surface of the reconstructed object will correspond to all points *x* such that $f(x) = .0$

- Constraint points specification. As discussed in Section 4, a RBF-based implicit function is modeled through the specification of (1) a set of boundary constraint points {qi} and (2) a set of normal constraint points {ni} together with their associated scalar values {wi}. The vertices of *E* and *P* are used as the boundary constraint points. Afterwards, for each vertex vi of *P* a normal vector is estimated and a normal constraint point ni is generated, displacing vi a small distance *d* along that vector. The normal vector is estimated by the sum of vectors a+b, where a= vi-1 -vi and b= vi+1 -vi. The normal constraint points ni corresponding to the vertices of the front skeleton are generated in the direction of the vector (0,0,1) and displaced a distance *d* along that vector. In the same way, those that correspond to the vertices of the back skeleton are generated in the direction of the vector (0,0,-1).
- Construction and solving of the equations system. Once sets {qi} and {ni} are computed, we build a linear equation system (see (Turk and O'Brien, 2002)). For the constraint points that determined the surface of the model we use w=0 for as the value of the implicit function, and the value of w=1.5 for those that determine the surface orientation. Lastly, the equation system is solved using a standard LUdecomposition method.

5.3 Visualization

Finally, the zero level iso-surface of *f* should be visualized. For this purpose, we use a variant of the poligonizacion algorithm proposed in (Lorensen and Cline, 1987). The obtained polygonal mesh is appropriately illuminated and visualized using standard graphics hardware (see results in Figure 3).

6. RESULTS

The algorithms described in the previous section were applied to the pictures presented in the Figure 1 with the purpose of obtaining the 3D reconstruction of the corresponding zoomorphic geoglyphs.

All the images used in the experiments were obtained on the Internet. We selected those pictures that presented good contrast --which allowed us to identify the silhouettes without more complications-- and mainly those that were generated from a perpendicular direction to the surface where the geoglyph is located.

The images shown in Figure 3 present different pictures of the reconstructed models. These images were generated starting from different view points of the observer with regard to the corresponding model.

7. CONCLUSIONS

The characteristics of the obtained models suggest that the strategy adopted for the 3D information generation --the elevation of the skeleton-- produce quite reasonable results. The interpolating approach adopted for the generation of the models was able to convey the soft aspect inherent to organic beings existent in the nature. This contributes to increase the expressive power of the models.

Due to the particularities of the problem, in particular the absence of three-dimensional information in the pictures, the quality evaluation of the reconstructed models is highly subjective. The fact that the obtained models don't represent real animals exactly, in no way diminishes the merit of this work, since the only available information for the reconstruction process was the silhouettes obtained starting from the aerial photographs.

It is important to stress that the quality of the used pictures influences directly the quality of the obtained results. When we speak of quality we don't refer solely to the contrast level in the pictures, but also to the position from which they were obtained. In other words, the more perpendicular to the geoglyph surface is the observer's position (camera), the better were the obtained results.

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REFERENCES

Arrieta, J., 2004. El enigma de nazca. http://www.arp-sapc.org/articulos/nazca.html (accessed 2004 Setember).

Association Dr. M. Reiche, 2004. The Lines and Geoglyphs at the Pampa of Nazca/Peru. http://www.htw-dresden.de/~nazca/ (accessed 2004 Setember).

Aveni, A., 1990. The Lines of Nazca. Memoirs of the American Philosofical Society. Vol 183.

Bajaj, C., Blinn, J., Bloomenthal, J., Cani-Gascuel, M., Rockwood, A., Wyvill, B., and Wyvill G., 1997. Introduction to Implicit Surfaces. Morgan K. Publishers. California, USA.

CNN, 2004. Cable News Network. Reading between Peru's Nazca Lines. Tourists, grave robbers, tractor trailers leaving their mark. http://www.cnn.com/2004/TRAVEL/DESTINATIONS/02/12/apn.nazca.lines.ap/ (accessed 2004 Setember).

Dinh, H. Q., 2000. A Sampling of Surface Reconstruction Techniques. Georgia Institute of Technology.

Igarashi, T., Matsuoka, S., and Tanaka, H., 1999. Teddy: A sketching interface for 3D freeform design. In Proceedings of SIGGRAPH 99, pages 409–416. ACM Press.

Lorensen, W. and Cline, H., 1987. Marching cubes: a high resolution 3D surface construction algorithm. Computer Graphics, 21(4):163-169.

Menchola, J. (1990). Nasca. El Amor de Maria. Lima. Concytec-Perú.

Project Nasca/Palpa, 2004. Photogrammetric Reconstruction of the Geoglyphs of Nasca and Palpa. http://www.photogrammetry.ethz.ch/research/peru/. (Accessed 2004 September).

Reindel, M., Isla, J., and Koschmieder, K., 1999. Vorspanische Siedlungen und Bodenzeichnungen in Palpa, Sud-Peru Asentamientos prehispanicos y geoglifos en Palpa, costa sur del Peru. Beitrage zur Allgemeinen und Vergleichenden Archaologie, (19):313–381.

SAN 2004. Servicio Aerofotografico Nacional. http://www.fap.mil.pe/Grupos (Accessed 2004 September).

Savchenko, V., Pasko, A., Okunev, O., and Kunii, T. 1995. Function representation of solids reconstructed from scattered surface points. Computer Graphics Forum, 14(4):181–188.

Taubin, G., 1995. A signal processing approach to fair surface design. In International Conference on Computer Graphics and Interactive Techniques, pages 351–358, New York. ACM Press.

Turk, G. and O'Brien, J., 1999a. Shape transformation using variational implicit functions. In Proceedings of SIGGRAPH 99, pages 335–342. Held in Los Angeles, California.

Turk, G. and O'Brien, J., 1999b. Variational implicit surfaces. Technical report, Georgia Institute of Technology.

Turk, G. and O'Brien, J. 2002. Modelling with implicit surfaces that interpolate. ACM Transactions on Graphics, pp 855- 873.

TWT, 2004. The Washington Times. Peruvian mystery in danger. http://washingtontimes.com/world/20040419-093630-7670r.htm. (Accessed 2004 September).

UNESCO, 1994. Lines and Geoglyphs of Nasca and Pampas de Jumana. http://whc.unesco.org/nwhc/pages/doc/mainf3.htm. (Accessed 2004 September).

Velho, L., Gomes, J., and Figueiredo, L. H., 2002. Implicit Objects in Computer Graphics. Springer Verlag, New York.

Vigo, M., 1997. An improved incremental algorithm for constructing restricted delaunay triangulations. Computer and Graphics, 21(2):215–223.

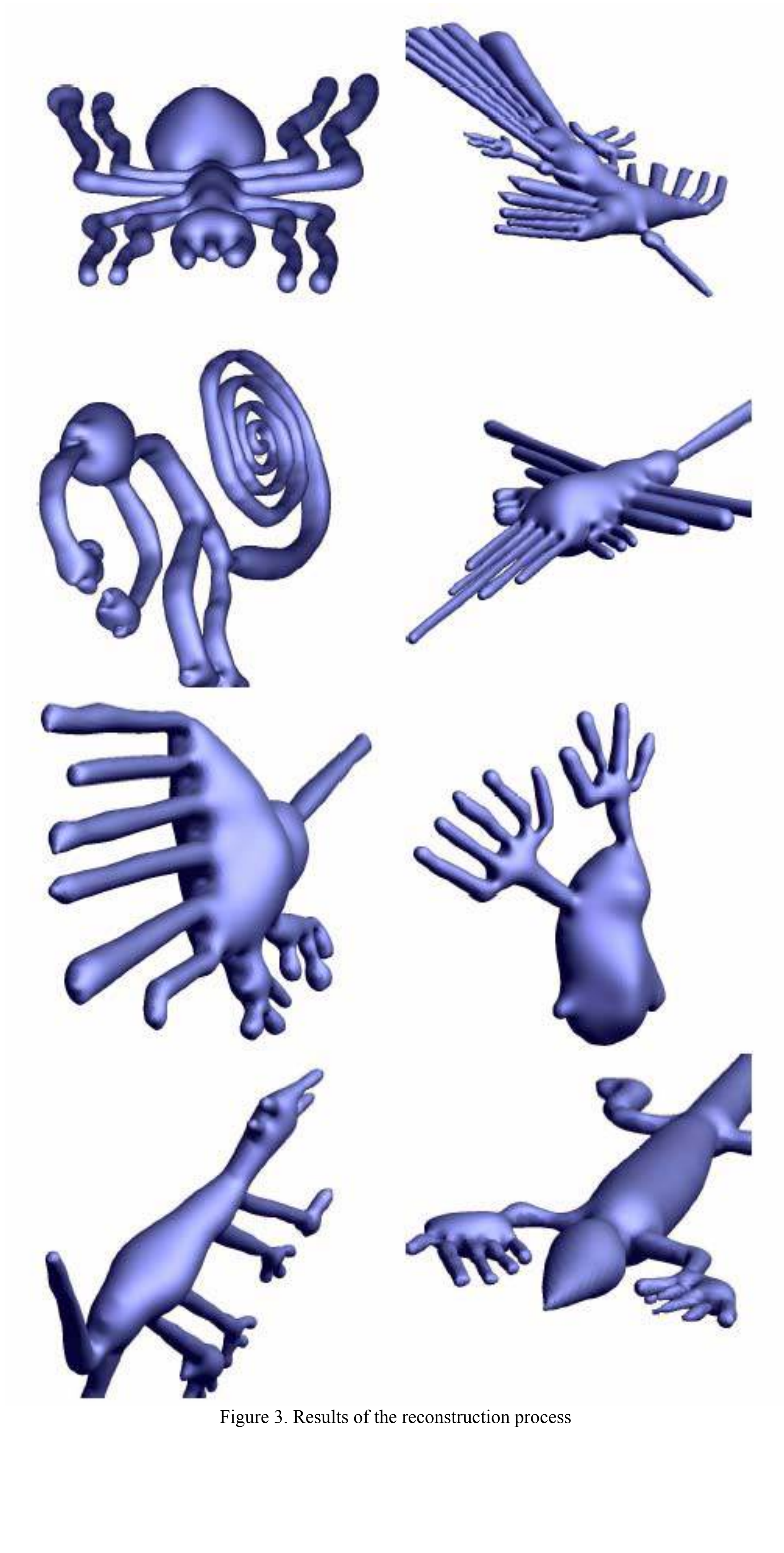

Figure 3. Results of the reconstruction process