The Use of Free-Form Deformation for Correcting the Taphonomic Distortions of Fossilized Hominid Crania

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ABSTRACT

This paper describes a technique for correcting the plastic distortion that fossilized crania found in South Africa are typically effected by. This distortion is caused by the collapse of the caves in which the fossils are deposited. The fossils are digitized using photogrammetry, resulting in a point cloud of surface positions. These positions then undergo statistical analysis (linear regression models) to determine their correct Cartesian location with respect to each other. Warping techniques are then used to correctly shape the skull.

Keywords

Free-Form Deformation, Computer Assisted Paleoanthropology, Cranial Morphology, Surface Splatting, Taphonomy

1. INTRODUCTION

Fossils are important to our understanding of human evolution. They provide evidence of our anatomical history, and offer us insight into our past behavioral patterns.

Unfortunately, many of the fossils that are found by Archaeologists and Paleoanthropologists are damaged or incomplete [3, 4, 9, 8]. In particular, here in South Africa the recovered fossils are often deformed in a plastic manner without any fracturing occurring [3].

This work is concerned with correcting such plastic deformations. The focus of this work is on correcting the distortion undergone by the fossilized crania (skulls) of our extinct ancestors and close relatives — these are the members of the *hominid* family, the group of primates who habitually walk bipedally, as humans do. We focus on crania due to their being the most diagnostic portion of the hominid fossil remains. By definition, all hominids walk upright, and this constraint on functional anatomy has caused the trunk and limbs of members in this family to change little in comparison to their cranial anatomy.

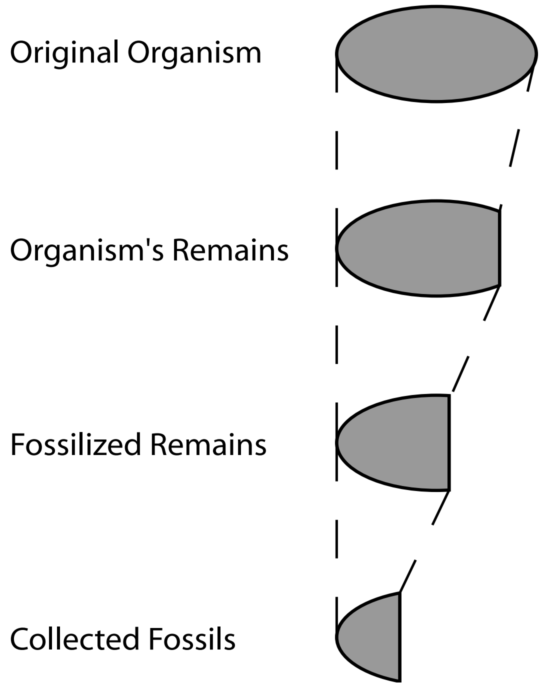

Figure 1: Information bias and loss. When an organism dies the death itself may bias the remains. For example, accident or disease may damage the bone. The remains itself may be transformed in some way: through decay, trampling, etc. Fossils may be eroded, distorted, fractured. Finally, those fossils that are found and collected may no longer accurately represent the original organism.

This paper will first discuss the causes of the fossil distortions. Next: the construction of computer models using photogrammetry, and the rendering of these models with splatting techniques. This is followed by an overview of the statistical techniques used to determine the correct position of the distorted elements, and a discussion of the warping techniques being used to carry out the correction. Finally, our testing regime is discussed.

2. THE PROBLEM

2.1 Taphonomy

In a palaeontologist's ideal world, an organism's death is soon followed by burial in soft, non-acidic sediments. Its remains would stay undisturbed, allowing the bone to chemically transform into rock — a chemical process called fossilization. Once exhumed, each bone would still retain its original shape and position relative to the other bones in the remains. Except for its chemical composition, the remains would be ready for study by all interested parties.

Most remains, however, are continuously acted upon by the environment in a manner above and beyond the two chemical processes of rot and fossilization. Carnivores eat off the carcass, chew and break the bones; remains may be trampled; the skeleton can become disarticulated and the bones scattered, or perhaps damaged by wind and rain or tunneling microorganisms.

Ultimately, fossil remains can reach a state were they are no longer an accurate representation of the original organism (see figure 1): all the changes that are introduced after death create what is essentially noise in the fossil's information content. This 'noise' masks the information we are most interested in, the information concerning the original organism's anatomy and morphology (shape).

In light of this, it is important that before studying any remains we determine what changes (if any) may have occurred to them after the organism's death. And to this end the field of *taphonomy* was introduced. Taphonomy (the 'laws of burial') is the study of the differences between a a living organism and its remains [10].

2.2 The taphonomic effects of caves

Most South African hominid remains are associated with caves (see [4, 3], for instance, for coverage of some South African sites). Caves are good accumulators of animal remains, being used by predators as dens [3] and often serving as traps that animals fall into from the surface [10]. Caves also offer an environment where the remains are sheltered from many of the agents affecting change. However, caves are not perfect. They have a finite lifespan and eventually erode and collapse, placing immense compression on any fossils buried within. Cave floors may erode away, causing any fossil containing sediments to collapse. Fossils trapped under such pressure may not necessarily fracture, but often distort in a flowing, plastic manner [3].

Being hollow, crania are fragile remains. Unless they fill up with sediments, collapsing caves can easily crush them under the immense pressure that they bring to bear.

Caves, then, have a duel edge. On the one hand they offer a rich supply of fossilized remains, but at the same time they can damage these same remains so that their study becomes immensely more difficult.

The history of changes that an organism's remains have undergone reflects the informational *bias* of the remains, a bias against both reconstructing and then reasoning about the original organism. This means that the first step to studying the remains is to remove this biasing effect, or, at least, to minimize.

3. DATA ACQUISITION

This work is carried out with 3D models of hominid crania obtained using *close range digital photogrammetry*.

Photogrammetry is a technique for locating points in space using photographs. When a point occurs in multiple images, information about the camera (such as its position and lens parameters) can be used to determine the point's position.

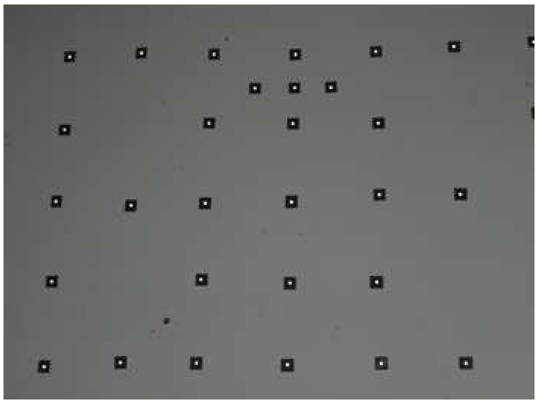

Figure 2: The calibration points used when calibrating the camera. The position of these points are known with a high degree of accuracy. This information is used to determine focal properties of the camera, including distortion parameters.

The technique used here proceeds as follows [16]:

A rectangular frame made up of steel tubes attached with retro-reflective targets is used as a *reference frame*. The position of the targets are known beforehand, and the crania placed within the frame when photographed. These points are then used to determine the camera's position for each photograph.

The camera is calibrated on a separate set of control points (see figure 2): in other words, information concerning the lens and its focal properties, including how it distorts the image, is determined.

Once the camera positions have been calculated, we then locate points that we are interested in finding a 3D position for. These are termed *interest points*. Since many interest points are needed per side (in the order of thousands: the face of the famous Mrs. Ples crania is modeled with over 5000 points), these interest points are first automatically located in one image using a *sobel filter*. They are then located in the other images by searching along the Z-Axis of the first image after projection into the other images. The point's final position in the image is then determined by matching small image areas to each other (although these areas need to be projected into each other, as they are taken from different positions).

4. SPLATS

As an output of the photogrammetric reconstruction we receive a dense point cloud set (typically, a single cranium is modeled with over 50 000 points). This data is ideally suited to rendering using *point splatting techniques*. Splatting is capable of rendering both volume and surface data [12] — in this case we are using it to render surface data. Surface data is data acquired from devices such as laser scanners and, as its names suggests, describes only a surface. Volume data is usually acquired through medical imaging techniques such as CT scanning, and has associated density information. Splats are used to spread the contribution of a sample (here, a texture sample) to the area around it. In this way points with associated texture information can be used to render whole surfaces even when lacking the information concerning how the points connect to form the surface. Specifically, we are currently the technique of Zwicker *et al.* [20] as our rendering method.

The work of Zwicker *et al.* is essentially an extension of Heckbert's work [6] dealing with techniques used for texture mapping. While Heckbert dealt with polygonal surfaces such as those made up of triangles, Zwicker extends this technique to work with points sets.

For the graphically inclined reader, the surface splatting algorithm of Zwicker *et al.* proceeds as follows:

```
for each point P
  project P to screen space
  determine the resampling kernel
  splat the kernel
for each pixel x in the Frame Buffer
  shade x
```

The point P is the object space point that is to be rendered. The resampling kernel is used for both filtering the texture [1] and sampling the texture. Zwicker *et al.* use an *Elliptical Weighted Average (EWA) filter*. This is essentially a filter with an elliptical region and a Gaussian profile.

The kernel is centered at the screen space coordinate of P, and evaluated for each pixel it covers. Overlapping regions are added to an accumulation buffer, so that their contribution to the surface rendering is blended (with their blending weight determined by the resampling filter).

5. CORRECTIVE TECHNIQUES

In common with many other fields, Paleoanthropology and Archeology have begun to use computers to assist in their reconstruction of the past (see [8, 17, 18] for reviews and examples). Most notably, they have been used to reconstruct fragmentary fossil specimens, recreating missing fragments using mirroring operations [18, 19].

Apart from reconstructing 'static' distortions (missing and misplaced fragments), statistical methods have been employed to correct more plastic distortions — distortional effects similar to those of interest here [13].

5.1 Statistics

For example, the work of Rasmussen *et al.* [13] is concerned with techniques for reconstructing the crania of a species of anthropoid called *Catopithecus browni*. *C. browni* was a tree-living quadruped the size of a small, new world monkey, that fed off fruit and insects. The best known crania of this species are all severely crushed. Their work compares the physical reconstruction of a composite crania, using molds made from portions of the crania of two separate individuals, to a statistical reconstruction.

Of interest is their second technique, which is quantitative in nature. Rasmussen *et al.* created a composite cranium based on landmark[2] data taken from two separate *C. browni* individuals and 951 tamarins. The tamarins were used in estimating the missing information concerning the anatomical relationship between the landmarks. They were chosen since the cranium of *C. browni* is considered comparable to smaller-bodied callitrichids such as the tamarins.

[1] This is done to avoid developing aliasing artifacts — such as those due to a texture not being properly band limited in its frequency domain [6] — from occurring on display.

[2] Landmarks are positions on an organism's anatomy that are well defined (they usually have names or labels) and have measurable Cartesian coordinates [2].

Rasmussen *et al.* began by finding the position of landmarks on the sutures [3] of the two original *C. browni* crania. Distances were measured between those landmarks that still kept their anatomical relationship to other landmarks — because each of the crania were crushed, this occurred only over small areas, and so most distances between the landmarks of interest could not be measured. Rasmussen *et al.* then measured the same set of landmarks (31 in total) on 951 tamarins, 498 individuals being from the species *Saguinus fuscicollis* and 453 from *S. oedipus*. The distances between landmarks where also measured.

The information obtained from the two tamarin species allows for the reconstruction of two separate models of *C. browni*, labeled *Cato-Fusc* and *Cato-Oed*. These models are created by first estimating the missing distance information for *C. browni* using regression equations (General Linear Model), with the known *C. browni* distances as independent variables. This regression analysis is concerned with the previously calculated euclidean distances, and at the completion of the analysis these distances are converted to Cartesian coordinates using multidimensional scaling. It is important to note the use of distances in the analysis rather than absolute positions.

This technique was tested both by reconstructing three complete tamarin crania using the same tamarin data set, and by comparing the landmark positions in Cato-Fusc and Cato-Oed to each other. They concluded it likely that the method reconstructed a complete cranium for *C. browni*. When reconstructing the tamarin crania, errors ranged from 0.5mm to just under 1mm. The average error for the reconstruction (as determined by looking at the known landmarks and their predicated values) using *S. fuscicollis* was only 0.026mm, and 0.049mm for *S. oedipus*. Rasmussen *et al.* concluded that reconstructing *C. browni* using tamarin morphology worked at least as well as it did when reconstructing the tamarin crania.

We will be extending the technique of [13] to reconstruct not just a subset of the possible landmarks found on the crania, but to reconstruct the whole cranium. Their technique can already be used to correct well known landmarks; all that remains is to extend the corrections to the area of the crania surrounding these landmarks, and *warping* techniques appear capable of doing this.

5.2 Warping

The seminal example of warping, free-form deformation (FFD), was developed to help increase the modeling flexibility of Solid Modeling [14], which is a set of techniques used for representing an object in such a way that it has a well defined interior and exterior. Solid Modeling was not considered as flexible as the more general surface modeling techniques (such as parametric patches)[4]. To help alleviate this problem, Sederberg and Parry developed FFD, a technique that literally warps an object by warping the space around it. Sederberg and Parry liken it both to a technique of sculpting for solid models, and to the process of embedding a flexible object into a volume of equally flexible plastic and warping the containing plastic volume in order to warp the object itself [14]. See figures 3 and 4 for examples.

[3] *Sutures* are the immovable joints on the cranium that connect the cranial bones.

[4] Solid Models are similar to real world objects: they each have a well defined 'inside' and 'outside'. It is possible, however, to model objects that have no interior. These are modeled using surface modeling techniques rather than Solid Modeling techniques.

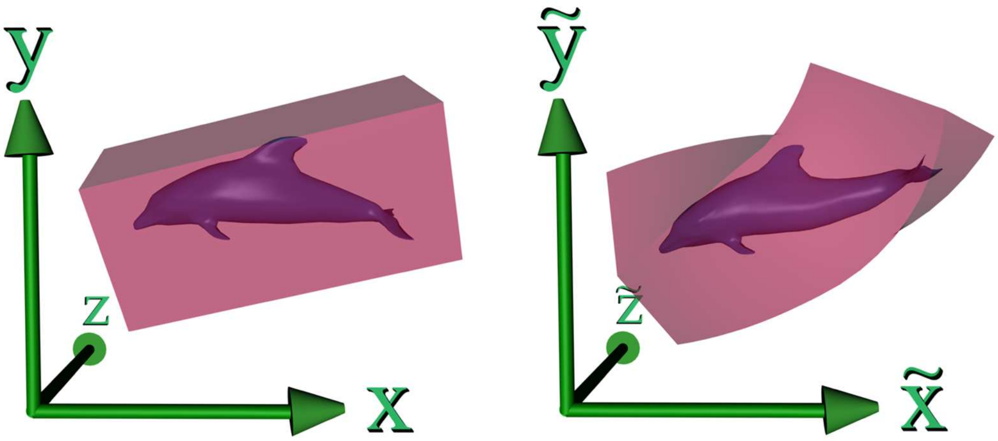

Figure 3: An example of FFD. The dolphin is embedded within a volume, and the volume warped. The warp is then transmitted to the dolphin.

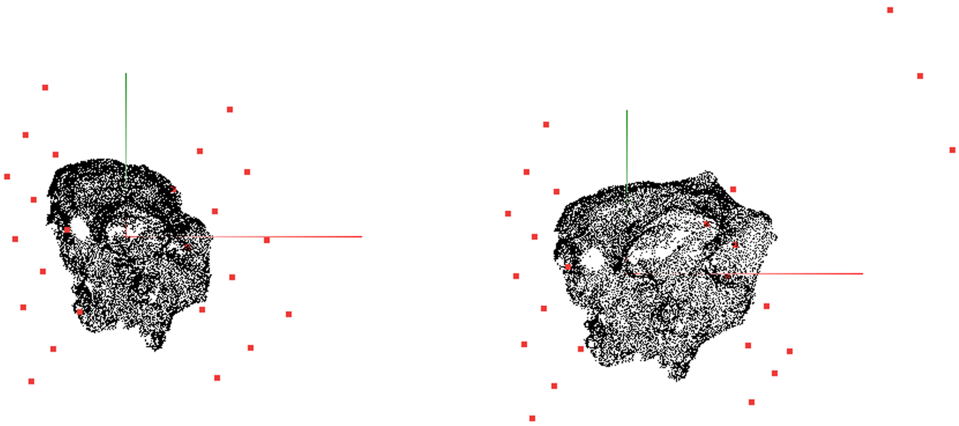

Figure 4: Another example of FFD, this time on a point cloud generated from the fossil SK 48. The red points are the control points that define the shape of the embedding volume (not shown). When the control points are moved, the point cloud changes shape.

Mathematically, FFD functions by embedding objects within a volume defined by the product of three polynomials[5]. The shape of this embedding volume is controlled by set of points aptly named control points. As these control points are moved, the embedding volume changes not only its shape but also the shape of all the objects embedded within.

Although Sederberg and Parry introduce FFD as a means of simplifying Solid Modeling, their technique is applicable to many more geometric representations than Solid Modeling, including parametric surface patches, implicit surfaces, and, as in our case, point clouds.

FFD was soon followed by other techniques meant for similar contexts: the plastic deformation of an object using a metaphor akin to sculpting. Early techniques included *extended free form deformation* [5], which generalizes the shape of the warping volume, and *directly manipulated free form deformation* [7] (DMFFD). DMFFD provides an alternative to the unintuitive process of control the shape of an object through control points. Instead, it allows the user to select a point (usually a point on the object, but the point can practically lie anywhere within the space of the embedding volume) and move the point directly. DMFFD then calculates the movement of the control points that would be required to produce such a change in that point. The deformation associated with this change in control points is then performed. This movement is minimal in the least squares sense.

For good summaries and a unified framework for the development of warping techniques, see [1] and [11].

6. OUR TECHNIQUE

6.1 General

Our technique takes a similar approach to that of Rasmussen *et al.* [13], however we attempt to extend it further. [13] essentially 'filled' in missing morphological information by looking at members of a similar species. Instead of this, we hope to use a mixture of [13] and warping techniques to restore damaged cranial regions.

Rasmussan *et al.* provides an ideal way to estimate correct positions for landmark data. This will give a general impression of a cranium's shape. Our work will use the technique of [13] to 'move' landmarks which have been determined (by a human user) to be in an incorrect position into their 'correct' position. These corrective movements will be used as input to a DMFFD warp. This will have the effect of warping the surrounding, damaged area back into a position estimated as being closer to the correct cranial morphology.

6.2 Testing

The technique itself will be tested on a cast of an undamaged cranium. The cast will be physically distorted and the reconstruction compared to the original. It will be important to attempt distorting the cast in such a way that the distortion appears similar to those applied by a collapsing cave. This will, unfortunately, have to be done by hand. If successful, this test will provide a good circumstantial indication of the technique's success.

However, being only a single test case, this does not provide any surety that the technique will work in general. To gain such surety, point cloud models of undamaged crania will be distorted and then corrected, giving descriptive statistics of average errors (and how these differ from expected errors) and so forth. The only concern is that the point cloud model of the undamaged cranium will be distorted using warping techniques similar to those used in correcting them. One possible solution to managing this concern is to model the deformation with a warping technique other than the one used in the correction, for example, with the use of *Wires*[15], a technique whose metaphor is based on the use of armatures in sculpting, armatures being curves placed on the surface of the model that guide its deformation.

[5]The functions used in classical FFD are the *Bernstein polynomials*. Three functions are used in order to define a volume — i.e. a function each for length, breadth and height.

7. CONCLUSION

Our work is the application of numerous research areas to a problem experienced in Paleoanthropology: the distortion of crania fossilized in cave deposits. Photogrammetry is used for modeling the crania, followed by the application of splatting techniques to render the model. Statistical analysis is performed to determine the correct positions of select portions of the crania, and warping techniques are used to perform the corrections.

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