# SIMPLE SHAPE-FROM-SHADING IN THE DENTAL AND MEDICAL MEASUREMENT CONTEXT

H.L. Mitchell

School of Engineering, University of Newcastle, Newcastle 2308, Australia – harvey.mitchell@newcastle.edu.au

**Commission V**

**ABSTRACT:**

Stereo-photogrammetric intra-oral measurement of teeth has been reported previously to be worthwhile to dental research, but inherently difficult because of the lack of optical texture in the dental surfaces. Shape-from-shading (SFS) from single imagery suggests itself as an alternative technique for dental measurement simply because a lack of texture is a fundamental necessity for shape-from-shading measurement. Furthermore, because a number of areas of the human body, notably the back which is of interest in scoliosis studies, can lack strong texture, shape-from-shading is an attractive prospect for various other medical measurement tasks involving human body surfaces. Despite some immediate attractiveness, shape-from-shading has difficulties which may effectively preclude reliable measurement by single images in real medical situations, and the prospective medical user of SFS needs to be aware of certain challenges. Despite these problems, in certain cases where the object is defined by simple shapes, such as may be encountered in incisor teeth and other common external body areas, some three-dimensional results can be achieved. This paper examines some of the possibilities and pitfalls with dental and medical body measurement using simple shape-from-shading, and shows some result from imagery obtained on extracted teeth, on living teeth in the mouth and in other human measurement cases, in which the gaol is to obtain useful, precise, three-dimensional surface data.

## 1. BACKGROUND

The recording of tooth shape is not an uncommon dental practice. Clinicians keep teeth replicas as records of patients' dental conditions, sometimes to enable them to observe change. They also make copies to permit the fabrication of crowns and inlays. And dental researchers study tooth shapes to investigate material loss due to various dental conditions. However, the recording of the three-dimensional shape of the teeth for such purposes invariably involves making castings of the teeth and, most often, the subsequent making of replicas from the castings; clinicians keep records of patients' teeth by storing the physical replicas; manufacture of crowns and inlays is based on physical shape duplication. Measurement (or digitisation) of the living teeth intra-orally to enable the keeping of digital records is useful but not yet practicable for most clinician. More commonly, the measurement is done either by laborious mechanical methods using styli (e.g. Chadwick *et al.*, 1997), or by optical/imaging methods. The feasibility and value of optical intra-oral measurement is signified by intra-oral measurement systems (D4D Technologies, 2010, Sirona, 2010), even though they measure using optical but not photogrammetric principles, but their price remains prohibitive for normal practitioners (fewer than 50 practices use the Sirona CEREC system in Australia, according to the Australian Society for Computerised Dentistry Inc., 2008), their high capital cost being seen as at least partly attributable to the use of triangulation and laser scanning, and attests to the need for a lower cost photogrammetric system.

Quick and minimally invasive optical intra-oral measurement would enable direct quantification of tooth shape, and would also significantly overcome the tedium of casting and replication procedures for patients as well as practitioners. Direct measurement of the teeth would obviate the casting and replication stages, but intra-oral measurement is currently not generally affordable.

There may therefore be a demand for intra-oral measurement which could be filled by photogrammetry, which has been applied to the measurement of many small objects, even the measurement of dental replicas, (e.g. Grenness, 2008). Photogrammetry seems to offers a reduced cost technique and which also avoids the need for castings. However, as explained by Mitchell and Chadwick (2008), intra-oral photogrammetric measurement is inherently difficult because of the lack of optical texture in the dental surfaces.

If photogrammetry faces difficulties, then shape-from-shading (SFS) from single imagery suggests itself as an alternative technique for dental measurement because a lack of optical texture is a fundamental necessity for shape-from-shading measurement. Furthermore, in the intra-oral dental situation, SFS has the advantage that it requires only one camera position to found within the cramped confines of the mouth. Moreover, a number of areas of the human body, notably the back which is of interest in scoliosis studies, can lack strong optical texture, so shape-from-shading is an attractive prospect for various other medical measurement tasks involving human body surfaces.

SFS has the advantage of being cheap, because it simply requires a single camera and light source. On the other hand, SFS has difficulties if the surfaces are irregular or not of even texture. Although teeth and the human body are both convoluted in shape, the localised surfaces of both teeth and the human body which are of interest for measurement can often be broken down into fairly evenly shaped patches of even texture. This paper trials SFS in some dental and medical cases, and shows that in cases where simplicity is possible, some uses are suggested and may be possible.

## 2. CONCEPTS OF SHAPE-FROM-SHADING

The basic concept of SFS is simple: the intensity recorded from reflections at a surface is given by the cosine of the angle between the reflected ray and the ray from the source, but for simple formulation the surface must be subject to Lambertian reflection, by which the light hitting the surface, which is partially absorbed and partially transmitted, is done so equally in all directions. According to Zhang *et al.* (1999), for pure Lambertian reflection:

$$R = A \rho \cos \theta \qquad (1)$$

where $R$ is the reflectance, $A$ is the strength of the light source, $\rho$ is the albedo of the surface, and $\theta$ is the angle between the surface normal and the source direction. The recorded intensity can therefore be used to deduce the angle between the incident ray and the normal, hence giving the angle between the reflected ray and thus the angle between the normal and the slope of the surface, relative to, say, the optical axis of the camera. SFS could thus be explained as slope-from-shading, and from the slopes, shape can be reconstructed.

## 3. DIFFICULTIES WITH SHAPE-FROM-SHADING

Despite some initial attractiveness, shape-from-shading does not offer a solution which is as direct as is ray intersection from multiple images, which is the basis of conventional photogrammetry. Its difficulties may well preclude more general widespread and reliable measurement by single images by SFS in real medical situations, and the prospective medical user of SFS needs to be aware of certain challenges:

1. The surface must be illuminated by an even light source.

2. The camera and light source should be coincident, for simple formulation of the geometry.

3. The reflection angle deduced by SFS is an indication of the direction of the surface normal relative to the camera's optical axis, and this direction is two dimensional, therefore requiring two parameters for the direction to be defined. Because the reflectance provides only a single data value, a solution for surface shape is impossible - unless assumptions can be made about the surface characteristics.

4. The solution for the slope from the recorded image intensity involves the inverse cosine, which is close to unity when the slope angle is close to zero, i.e. when the camera axis is approximately normal to the object surface, as it often is. The solution for the slope angle is then sensitive to noise in the reflectance value, causing excessive variations of deduced surface normal direction. Noise in the reflectance value can even cause the cosine of the slope to appear to be greater than unity, making the solution for the slope angle impossible. The solution involving the inverse cosine is also complicated by uncertainty of the sign when there are changes in object surface slope, and the cosine fluctuates around a value of unity.

5. Outliers due to regions of bright reflection can interrupt the solution, and thus disrupt the surface shape solution

significantly, (while also implying that the pure Lambertian reflection assumption is not valid).

6. The solution for the surface normal direction from the reflectance data is a function of $A$ and $\rho$, which can vary with the object. The relationship between reflectance level and albedo also needs to be held constant, by using standard photographic conditions or fixed camera settings. Automated digital camera settings with dental cameras can therefore create difficulties.

7. Both SFS and photogrammetry require good imagery, but SFS also depends on a good small light source close to the imaging lens, and this can create difficulties working within the confines of the human mouth.

8. Scale is not provided if only one camera image is provided.

## 4. SOLUTIONS

Solutions to the above problems, such as the imaging geometry, are fairly obvious. For the dental and medical experiments reported here, solutions to the some of other problems have been obtained as follows:

1. The problem of the three-dimensionality of the direction of the surface normal can be overcome if some information about the shape of the surface is available. Here, the analysis has been based on a single profile of the surface in which the direction of the normal is known to lie in a plane.

2. Noise has been smoothed by solving for a mathematical function which models the broad surface shape, rather than solving for particular slopes from individual pixels.

3. Cameras with manually controllable aperture rating and exposure time, or equivalent parameters, can help control the albedo-reflectance relationship.

The model can be tested using an object of known shape. A determination of the light strength and albedo parameters and the parameters representing the geometry of the light source and camera has been carried out using a flat object.
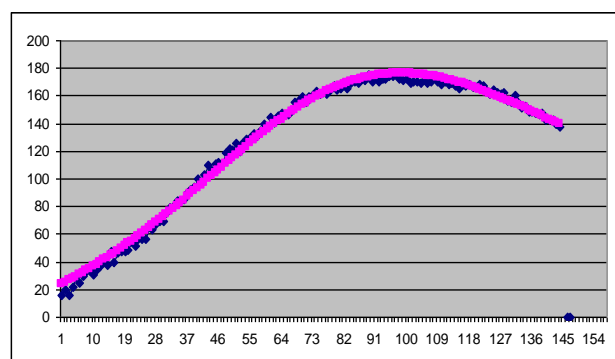


Figure 1: Observed reflectances compared with modelled reflectances, recorded on a flat white card recorded by a Flexiscope Piccolo intra-oral dental camera. The image has been reduced to 144 pixels along the axis.

In this case, a piece of flat white card was imaged using an Flexiscope brand Piccolo intra-oral dental camera, which provided 768 x 576 pixel colour images. A least squares solution was obtained for the parameters, and Figure 1 shows the agreement obtained between the measured reflectances on a flat object and those calculated using the reflectance model at Equation (1). The calculation is based on a profile along the $x$ axis of an image to overcome the problem of the two-dimensionality of the normal. The reflectance model was then tested on human dental and medical surfaces.

## 5. CASE STUDY 1: EXTRACTED TOOTH

To examine the possibility of using SFS to determine object shape, an investigation was undertaken on an extracted tooth in order to avoid difficulties of using live patients. The imagery was obtained with the Flexiscope Piccolo intra-oral dental camera referred to above. The tooth was aligned so that its axis was essentially along the long axis of the image in a landscape style image: see Figure 2. The solution was obtained by restricting the analysis to a profile along the $x$ axis of the image, thereby avoiding the problem of normals which are not in the plane of the profile. A parabolic curve was fitted to the tooth, in a solution involving the three imaging parameters required in the model plus the two parameters of the parabola. The result is therefore essentially an on-the-job calibration. The slopes which influence the reflectances were assumed to be the derivative of the parabola, or a function of $x$. The $z$ axis is assumed to be at right angles to the optical axis of the camera, and the $x$ axis is basically parallel to one edge of the image. The observed reflectances are compared with the modelled intensities on the tooth in Figure 3. Unfortunately, the results are extremely difficult to check because the tooth cannot easily be mentioned by an alternative means.
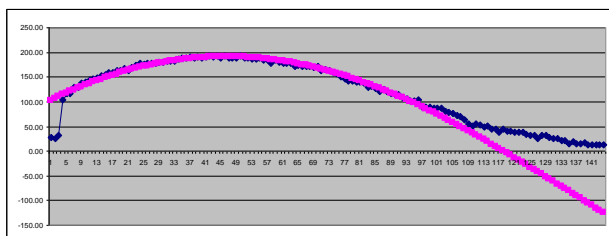


Figure 2: Extracted tooth image.



Figure 3: Observed reflectances compared with the modelled intensities on an extracted tooth.

## 6. CASE STUDY 2: INTRA-ORAL HUMAN TOOTH

A human tooth was imaged, again using the Flexiscope Piccolo intra-oral dental camera; see Figure 4. Again, the solution was obtained by restricting the analysis to a profile along the $x$ axis of the image, and a parabolic curve was fitted; the slopes were found and a profile deduced. The image is shown in Figure 4 and the results of the least squares fitting of a parabola are shown in Figure 5 as a comparison between the model reflectnaces and the observed reflectances.

## 7. HUMAN TORSO

As another medical area of interest, a human back was imaged, using a Canon EOS30D single-lens-reflex digital camera with a 28 mm Canon lens. Again, the analysis was restricting to a profile along the $x$ axis of the image where the normals could be expected to lie in a plane. However, no curve was fitted and slopes were deduced. The image is not shown in the interests of privacy, but a comparison between the model reflectances for a plane object and the observed reflectances is in the vicinity of the waist is shown in Figure 6. The reflectances reveal the expected changes around the arms as well as the torso, and the expected lack of reflectance between arms and torso, while a flat wall on the right hand side of the profile follows a predicted pattern for a plane object. Figure 7 shows the calculated slopes, with negative values to the left of the spine, as expected.
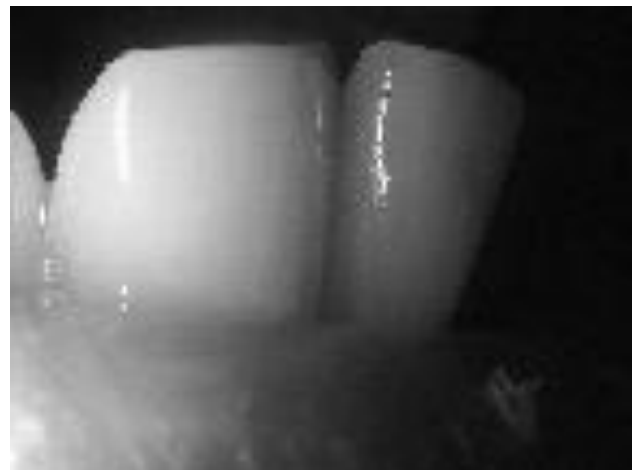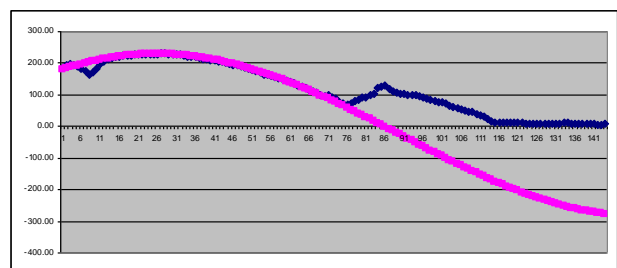


Figure 4: Images of teeth in a human mouth.



Figure 5: Observed reflectances compared with the modelled intensities on an extracted tooth. The change in intensity from one tooth to the next on either side is apparent on the profile of reflectances, as is the small peak representing the bright refection, where the surface is normal to the camera axis.
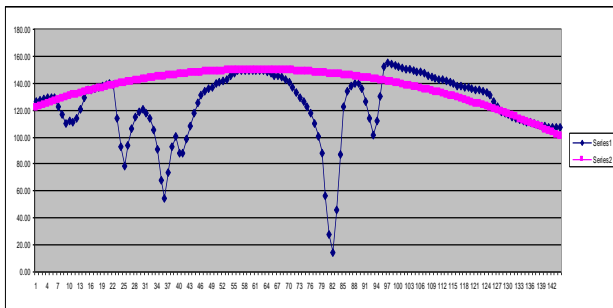
Figure 6: Observed reflectances compared with the modelled intensities on a human waist.
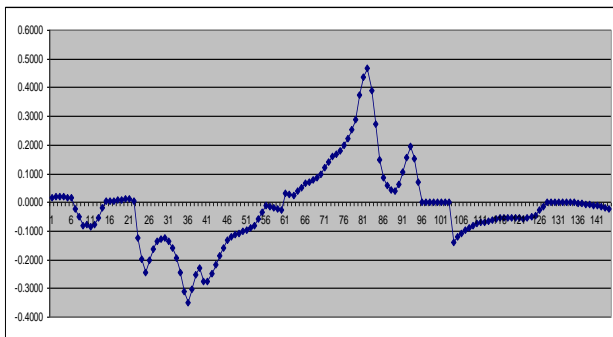


Figure 7: Calculated slopes across the waist of a human subject.

The results cannot realistically be confirmed but they simply suggest that realistic slopes can be determined by SFS for medical objects other than teeth.

## 8. DISCUSSION AND CONCLUSIONS

The results reported here are of an investigation into the feasibility of using SFS based on Equation (1). Simplifications have been made, primarily to combat the under-determined nature of the SFS solution, while secondly the varying nature of the reflectance parameters has been faced by using on-the-job determination of the parameters - which may not be acceptable in real dental and medical measurement cases.

Simple results obtained so far in this project relate only to profiles along an axis of each image, across the object, when this is seen as eliminating one unknown in the direction of the normal, and results have been unverified. The experiments imply that shape-from-shading is of such a complexity that in many cases, photogrammetry is no more difficult, and it may well be easier to develop photogrammetry than develop SFS for many purposes, especially as contemporary modern photogrammetric software is able to cope with complex imaging situations. The difficulties with SFS may effectively preclude reliable measurement by single images in real medical situations. Results show that the shape-from-shading model agrees with measured reflectances in simple medical and dental cases.

## 9. REFERENCES

Australian Society for Computerised Dentistry Inc., http://www.ascd.org.au/index.html

Chadwick, R.G., Mitchell, H.L., Cameron, I., Hunter, B., & Tulley, M., 1997. Development of a novel system for assessing tooth and restoration wear. *Journal of Dentistry,* 25 (1), pp. 41-47.

D4D Technologies, 2010. http://www.d4dtech.com, (accessed 4 April 2008).

Grenness, M.J., Osborn, J. E., & Tyas, M. J., 2008. Mapping tooth surface loss with a fixed-base stereo-camera. *Photogrammetric Record*, 23(122), pp. 194-207.

Mitchell, H. L. & Chadwick, R.G., 2008. Challenges of Photogrammetric Intra-Oral Tooth Measurement. In: *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Kyoto, Japan, Vol. XXXVII, Part B1, pp. 779-782.

Sirona 2010, http://www.sirona.com, (accessed 12 April 2010).

Zhang, R., Tsai, P-S., Cryer, J.E. & Shah, M., 1999. Shape from shading: a survey. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 21 (8), pp. 690-706.