

# CHALLENGES OF PHOTOGRAMMETRIC INTRA-ORAL TOOTH MEASUREMENT

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## ABSTRACT:

Recording the surface shape of a living tooth would seem to be a straightforward photogrammetric task, but the researchers' experiences in developing a procedure for routine intra-oral tooth measurement shows that, in practice, photogrammetric measurement of the living tooth in the mouth has difficult challenges which are predominantly photographic. Although the problem of access can be overcome by using specialist intra-oral dental cameras, arranging multiple images is problematic. A second challenge arises because of the optical characteristics of dental enamel: the tooth surface is featureless and is unsuitable for photogrammetric mapping without some augmentation, and the enamel is also highly reflective. Some imaging tests have been carried out on teeth in the mouth in the search for an automated measurement technique, but, to avoid patient discomfort, further investigations have been carried out on an extracted tooth, whose characteristics are similar to those of the live tooth. In an example cited here, a pair of images of an extracted frontal incisor was collected with a single camera, a camera base of about 6 mm and a base-to-height ratio of 1:2. To make the enamel surface both opaque and textured, it was painted with a weak water colour solution. Features detected with an interest operator were matched by area-based matching, and coverage was of acceptable accuracy and density except in areas of illumination glare. The measurement should be repeatable with living teeth by duplicating the conditions of the photography, but procedures with living patients are noticeably more awkward than working with inert objects.

## 1. INTRODUCTION

### 1.1 General

The ultimate goal of the work outlined here is to measure living teeth within the human mouth using automated photogrammetric methods. The work has begun with attempts to measure extracted teeth, as this clearly avoids the need for uncomfortable access to patients during continual experimentation. Recording the surface shape of a tooth would seem to be a straightforward photogrammetric task, but the researchers have found that, in practice, photogrammetric measurement of the living tooth in the mouth, and even the extracted tooth, has a number of distinct and difficult photographic challenges. This paper reports some of the experiences and progress of the researchers in initial attempts at developing a procedure for routine automated intra-oral tooth measurement.

### 1.2 Dental studies and uses of surface measurement

Measurement of the shape of living human teeth has beneficial applications in dental research, to enable researchers to quantify the loss of tooth surface material. This loss can be brought about by contact with acids produced by bacteria upon metabolising sugars in foods (causing dental caries/decay) or by direct contact with the tooth surface itself (dental erosion). It may also arise from mechanical wear and tear such as seen in abrasion or attrition. Considerable dental research effort is expended investigating each of these matters. The investigations into all of these issues frequently involves measuring teeth shapes at various epochs, in order to carry out comparisons which indicate the volume and distribution of decayed, eroded or abraded material. The studies can be expected to involve the measurement of statistically significant

numbers of teeth. Hence, it is arguable that dental research into tooth surface loss represents a realistic area of demand for measurement, and it is foreseeable that it could be undertaken photogrammetrically.

In addition, measurement of the shape of living teeth has applications for clinicians, primarily for the fabrication of crowns, as is borne out by the existence of commercial optical (but not photogrammetric) measuring systems (e.g., Sirona GmbH, 2008; D4D Technologies, 2008). The use of shape measurement for recording patients' dental histories is also imaginable, although this is not seen to be occurring at the moment.

It is assumed by the writers of this paper that the convenience requirements of a commercial measurement system for clinical use would be much more stringent than for research use, so it is the research use, including the writers' own dental research use, (e.g., Chadwick et al., 2005) to which these studies are currently targeted.

### 1.3 Current methods

Despite the extensive need for tooth measurement, direct intra-oral measurement can currently be prohibitively expensive. Consequently, measurement of the three-dimensional shape of teeth (whether for research or clinical use) normally proceeds by taking castings of the teeth and, most often, by the formation of replicas from the castings. The replicas are then measured, often by mechanical methods, using styli, or just occasionally by optical/imaging methods, including photogrammetry (Grenness *et al.*, 2008). To obtain statistically meaningful quantities of patient tooth measurements in an extensive investigation of dental erosion between 2001 and 2003, the

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writers of this paper measured approximately 500 tooth replicas using a mechanical stylus method, (Mitchell et al., 2003). Such a procedure is clearly very protracted and inefficient. Many other dental surface researchers carry out similar measurements, (see, e.g., Azzopardi et al., 2000; Bartlett et al., 1997; Mehl et al., 1997; Pesun et al., 2000; Pintado et al., 1997 ).

#### 1.4 Goal

It is seen as highly advantageous for dental research to be based on direct intra-oral measurement. Firstly, direct intra-oral measurement would overcome the tedium of the casting procedure for patients as well as dental workers. Secondly, the use of photogrammetry could improve the efficiency of the measurement procedure, as has been done for replica measurement (Grenness et al., 2008).

#### 1.5 Alternatives

Various techniques for dental replica measurement are imaginable. However, for intra-oral measurement, any instrumentation must meet severe access criteria, especially if any side of the tooth – not simply the most easily accessed – is to be measured. Electron microscope methods fail in this regard, as indeed do other methods involving microscopes. Among the optical methods, the obvious alternative is laser scanning but it faces a far high equipment expense than does photogrammetry. Other optical options include shape-from-shading, moiré fringing and structured light techniques. The feasibility and value of optical intra-oral measurement is signified by the CEREC (Sirona GmbH, 2008) and D4D (D4D Technologies, 2008) intra-oral measurement systems, even though they measure using optical but not photogrammetric principles. The cost of optical dental measurement techniques based on structured light patterns is hard to estimate, because the commercial units are sophisticated and moreover are available only when linked to crown machining software and hardware.

#### 1.6 Photogrammetry's advantages

Intra-oral measurement by optical methods seems to be a feasible option. Photogrammetric measurement can be executed at low cost, because the only significant hardware requirement is a camera. Intra-oral cameras are commercially available. Although there is a likely requirement for ancillary items such as lighting, lenses and mirrors, these are relatively cheap. The other significant photogrammetric components are software. Given the need for automation, and given the current sophistication of automated image matching, photogrammetry was seen by the writers to be deserving of some experimentation.

#### 1.7 Requirements

The above description suggests that there is a demand for development of a tool which could be used to measure any surface of any tooth in the mouth to aid any dental research which involves studies of the loss of the external enamel surface of the tooth. However, to replace alternative and existing procedures which involve taking castings, and perhaps replicas, of the tooth for subsequent measurement by mechanical or photogrammetric means, as is intended for such purposes as studying tooth surface loss caused by decay and/or erosion, the technique must be superior in other aspects as well. The requirements are therefore seen to be:

- Able to measure any surface of the tooth, this defining access requirements.
- Quick, comfortable and safe for the patient, i.e. easier than taking castings which can take a few minutes.
- Simple and easy for the dentist and/or researcher, and accordingly the photogrammetric measurement must be entirely automatic.
- Providing an absolute accuracy of about 0.01 mm in absolute terms. This accuracy represents a low relative accuracy of 1:1000 if the tooth is about 10 mm across.

## 2. THE PHOTOGRAMMETRIC DESIGN

### 2.1 Imaging

The problem of access to all teeth can be overcome by using commercial intra-oral dental cameras. This work is based on a Flexiscope Piccolo camera, providing colour imagery at 768 x 576 pixels size. Collecting suitable multiple images is a serious difficulty. If a single camera is used, movement of the camera in close proximity to the human patient while controlling translations and rotations of the camera relative to the patient can be difficult. The use of two cameras is therefore attractive; Grenness *et al.* (2008) decided that “*close range applications, by their compact nature, are well suited to fixed base stereo camera equipment. If the stereo camera is sufficiently rigid then, once fully calibrated, object space control is not required*”. However, the use of two cameras can severely limit access to certain regions in the mouth, and, moreover, the use of two separate cameras complicates image file handling, and this has also been seen as undesirable for this project. Good estimates of parallax values are also needed to get reliability and matching success, and this demands careful control of the camera position.

### 2.2 Calibration

The Flexiscope camera lens has a short but unknown focal length with a 105° of field of view (Inline, 2008) and, not surprisingly, high distortion levels, and it demanded calibration.

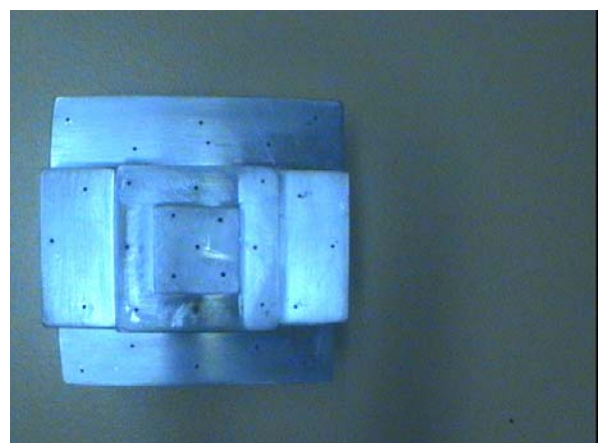


Figure 1. Intra-oral camera image of calibration object, only approximately 10 mm in size. Distortion is apparent.

Calibration is problematic with small objects. A determination of both principal distance and distortion parameters has been undertaken using a small in-house test object, approximately 10

mm in each dimension, on which 30 control points were available, as shown in Figure 1.

The pixel size and principal distance were unknown, so a pixel size of 0.01 mm was adopted. Calibration using PhotoModeler software (PhotoModeler, 2005) and eight images (see Figure 1 for an example) yielded a principal distance of 8.1 mm, and distortions which can be characterised by a radial distortion  $K_1$  value of 0.006, (so that imagery had a radial shift of 10 pixels at a radial distance of 400 pixels) and a tangential distortion  $P_1$  value of 0.00009.

### 2.3 Teeth as imaging objects

A major photographic challenge derives from the optical characteristics of dental enamel. It is featureless and is unsuitable for photogrammetric mapping without some augmentation. Tooth enamel is also partially translucent and yet highly reflective, the latter causing areas of glare, especially from the in-built illumination of an intra-oral camera. In addition, imaging difficulties are created by the inevitable coating of saliva.

## 3. CASE STUDY

Although a limited number of imaging and basic measurement tests have been carried out on teeth in the mouth, realistic measurement trials have been carried out on an extracted tooth to avoid patient discomfort. It is recognised that its optical characteristics are not necessarily identical to those of a live tooth.

In one of the more successful, and also one of the more informative cases, a stereo-pair of parallel images was collected of an extracted frontal incisor tooth. To make the enamel surface opaque and textured, it was painted with a weak water colour solution: see Figure 2. The resultant texture had no pre-designed shapes or patterns.



Figure 2. Right hand image from stereo-pair, taken at a distance of 17 mm from the tooth.

The tooth was moved a measured distance of 6.00 mm under the camera by using a translatable slide fitted with a micrometer. The tooth, which was about 8.5 mm across at its widest point, was imaged from a distance of about 17 mm, giving a scale of

about 0.025 mm per pixel. The base distance gave an overlap of 60% and a base-to-height ratio of 1:2.

Monochrome versions of the imagery were searched for features using an interest operator; each feature on the left image was paired with features on the right image on the basis of predicted  $x$  and  $y$  coordinate differences; points were then matched to sub-pixel precision by an in-house area-based matching algorithm. Matches were accepted if they exceed threshold values of correlation co-efficient and match precision.

## 4. RESULTS

A large number - about 450,000 - of candidate points were found using interest operator on each image. With acceptance values of a minimum 0.9 for the correlation co-efficient and a maximum 0.1 pixels for the match precision, about 600 matches on the tooth were accepted. However, the points were localised, as areas of low texture (including high reflection) affected a significant proportion of the field-of-view of the tooth. Moreover, the existence of good matches in the vicinity of the texture is very apparent, and emphasises the difficulty of texturisation; see Figure 3.



Figure 3. Distribution of 600 successful matches on a limited region of the tooth, shown superimposed on the monochrome left image. The paucity of points in the vicinity of glare and light texture is very apparent.

For this work, a single camera has been moved, by an amount which has been determined by a relative orientation using the PhotoModeler software which requires manual point selection (PhotoModeler, 2005), but this manual intervention is not an acceptable long-term option.

The precision of 0.1 pixels represents about 0.003 mm across the tooth, or a satisfactory depth precision of about 0.006 mm assuming a base-to-height ratio of 1:2. The true accuracy of the surface delineation has not yet been evaluated, and indeed it is hard to do so. Comparison with replicas by mechanical means involves a comparison with a technique of similar accuracy.

## 5. DISCUSSION AND CONCLUSIONS

The anticipated problems due to the size of the object, and calibration of the camera have been easily overcome. Automated photogrammetric procedures were successful enough to suggest that these matters are not a problem.

Photographic problems were encountered. These lay in camera manipulation to create a stereo-pair in controlled positions and the need for texturisation of the object to permit successful feature detection and matching. It was apparent that the texture was not as crucial to achieve success as it was to obtain acceptable reliability.

It could be expected that the measurement should be repeatable with living teeth by duplicating all the conditions of the photography, but operations on an extracted tooth are noticeably easier than working with live patients. Because the tests were carried out on an extracted tooth, the investigation is inconclusive but results are encouraging.

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