A 3D scanning system for biomedical purposes using the laser light-sectioning method and Elliptical Fourier Descriptors

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I. Introduction

The use of three-dimensional (3D) scanning systems for acquiring 3D models of objects has many applications in industry, computer graphics, and more recently, medicine. Biomedical applications of 3D scanning include orthodontic treatment planning [1], cranial deformation research [2], cartilage morphology studies [3], and anthropometric data collection [4]. The potential exists to expand the biomedical uses of 3D models even further, by continuing to develop simpler, more cost effective systems for acquiring external shape features of biological objects. There exists a variety of different techniques for acquiring 3D models of objects, all with a wide range of hardware costs, and differing levels of achievable accuracy and detail in the captured geometric models. A good review of 3D model acquisition techniques and the data processing pipeline can be found in [5].

We are looking for a simple 3D scanning system with the underlying goals of being cost effective and versatile. We have decided to focus upon the accepted technique of laser light-sectioning for this system. This technique involves measuring the position of an object's surface profile by recording where the profile intersects a plane of laser light. A key feature of the proposed system will be the ability of the camera and laser system to rotate about an object with the required number of degrees of freedom making it flexible for numerous applications; particularly for biomedical applications where the apparatus would ideally rotate about a patient and not vice versa.

When employing the laser light-sectioning technique, only a portion of the object's profile can be captured from any given angle. Therefore the object model must be reconstructed by connecting numerous segments of data into one complete contour. The data obtained from this technique is also quite noisy. We propose that Elliptical Fourier Descriptors (EFDs) are an appropriate technique for this system, both for fitting a single curve through the data segments and for reducing noise. According to [6], a 2D continuous closed contour can be represented by Fourier trigonometric series, the coefficients of which are referred to as EFDs. With these descriptors, a contour can be re-created at any time in the absence of the original data. EFDs have been shown to be particularly suited for biological objects, further supporting their use for a biomedical scanner. This has been demonstrated in [7], where they are used to fit contours of the prostate from a series of computed tomography (CT) scans in order to construct a 3D model, and in [8], where they are used to quantify the shape of human mandibles in order to analyze variability and sexual dimorphism between individuals.

II. Proposed Approach

A. General system setup and data acquisition process

The system setup is illustrated in Fig. 1. A laser diode (Lasiris Diode Laser) fitted with line optics creates a horizontal light plane (i.e. parallel to the xy-plane). The trace of light plane is visible when projected onto the object of interest and is recorded with a CCD camera (TM-200 High Resolution CCD), which is inclined at a fixed angle α (40° was used in this work), relative to the xy-plane. Images are captured with a NI PCI-1411 image acquisition device. The goal of each measurement is to obtain one segment of one planar section of the object.

A single planar section of the object is constructed by: a) capturing M views of the laser trace in the plane of the section, separated by rotations of R=360°/M about the vertical z-axis; b) transforming the laser trace segments using a transformation obtained from a calibration procedure to remove the projective distortion of the camera; and c) rectifying the laser trace segments to form an entire 360° outline of the external profile of the object. Further processing can be done at this stage to fit a smooth curve through all the segments; in this case the use of EFDs is employed. Repeating this process for N planar cross-sections and stacking them along z-axis results in a 3D wire frame outline of the object.

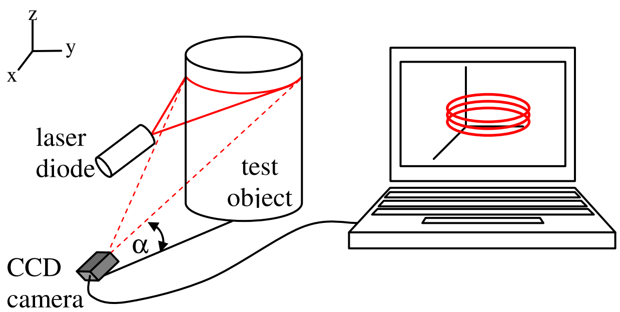

Figure 1: Laser light-sectioning system diagram

B. *Proof of concept experiment*

To demonstrate the validity of our approach described above, an experiment was conducted to reconstruct a small portion of a simple test object. The system to rotate the measurement head is still under development, necessitating manual manipulation for this preliminary experiment. Rather than manually rotate the measurement head, the equivalent problem was to rotate the object of interest.

Images for N = 4 planar sections of the test object were captured; this test object was a cylinder with diameter 19.05 mm (¾ in). For each plane M = 8 images of the laser trace on the object were captured in rotational increments of R = 45°. Planar sections were captured at 3.175 mm (⅛ in) increments in the negative z-axis direction. In total, 32 images of laser trace segments were captured for reconstructing the 4 planar sections.

For data processing, the following steps were implemented: first, using a simple background eliminating algorithm, thresholding, and an iterative thinning algorithm available in Matlab [9], a discrete set of point coordinates for each laser trace segment, representing the best path through the raw image, was determined. Then, the set of point coordinates for each segment was mapped to the Cartesian plane to remove projective distortion of the camera using a transformation matrix obtained from a calibration procedure. The 8 segments were rotated to their respective rotation angle and reassembled into planar sections about a suitable longitudinal axis. To reduce error in segment alignment, as suggested in [5], samples in overlapping regions were averaged producing a single complete contour for each planar section.

C. *Curve fitting with Elliptical Fourier Descriptors*

An EFD algorithm was used to fit a smooth curve through the points of each planar section. The theory of EFDs is as follows: a 2D continuous closed contour can be represented parametrically as a function of time, $V(t)$; projections of this vector function on the x and y axis, represented by $x(t)$ and $y(t)$, are periodic with period P, where P is the time required to trace the entire contour at a constant speed. These projections can be represented by Fourier trigonometric series, the coefficients of which are referred to as EFDs. Different levels of approximation to the closed contour represented by $x(t)$ and $y(t)$ can be obtained by truncating the Fourier series after different numbers of harmonics [10]. Complex object profiles are thus represented with higher order harmonics.

In this case, only 1 harmonic was required to accurately fit the calibration cylinder and test object (also a cylinder); however, higher order harmonics could be used to fit more complicated object profiles. The final object contours were stacked along the reconstruction z-axis.

III. Results

Fig. 2 is a plot of the radii obtained from the reconstruction process, both before and after the contour was fit with a smooth curve using the EFD technique. Only the first planar section is shown, however results were similar for all 4 layers that were reconstructed for this experiment. As indicated, the ideal radius in this case was r = 9.525 mm ($^3/_8$ in).

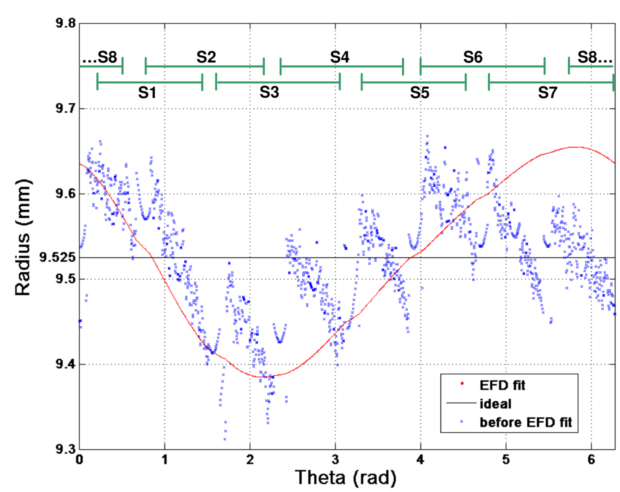

Figure 2: Profile of test object (cylinder with radius = 9.525mm). Radius shown as a function of theta from 0 to 2pi for raw data (constructed from 8 segments, S1-S8) and for EFD fit.

IV. Discussion & Future Work

As shown in Fig. 2, the rectified segments for the given planar section of the test cylinder appear to produce a fairly good result, even before a curve was fit to the data with the EFD technique. The percent error between the radius of the reconstructed test object and the actual radius of the object is about 1-2%. Errors do not exceed 0.25 mm. The subsequent EFD contour for this first layer shows a fairly close fitting through the points using only 1 harmonic.

Although sub-mm accuracy is achieved overall, there is observable noise in the error plot (Fig.2). This noise appears to be made up of a random noise component and a systemic noise component. Since no smoothing was performed on the data before the EFD fit, the random error could be due to noise inherent in the measurement system and noise in the resulting point coordinates obtained from the thinning algorithm. This noise is clearly attenuated in the EFD fit.

The systemic noise is present in the data both before and after the EFD fit. The most prominent sources of this error for this setup were procedural in nature such as inaccuracies associated with manually turning the object in its place. Also, in the unfitted data, one can observe obvious jumps in the radii obtained where segments were fused together and a general downwards trend in the radii for these different segments. This could be due to misalignment of the test object about the reconstruction axis after manually raising it with the gauge blocks, resulting in a slight shift in the segments. All of these errors are associated with limitations of the current setup, and will be attenuated or eliminated with future versions of the prototype in which the camera and laser diode head will be precisely manipulated about the object in an automated manner. Although the EFD does not appear to have a significant effect on the noise in these results, it is anticipated that it will once the systemic noise sources are addressed.

Due to the shape of the objects used for this experiment, the number of harmonics chosen to accurately fit the data using EFDs was 1. Further work is required to develop a preprocessing technique that would automatically identify an appropriate number of harmonics to use for a given set of data segments, since not all objects imaged would have circular symmetry as in this test case. This would result in accurate contour fitting without excessive data processing. Other methods are also being investigated for this system to account for cases where discontinuities in the laser trace exist (e.g. sharp edges).

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