Three-dimensional scanner based on fringe projection

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Abstract. This article presents a way of scanning three-dimensional (3-D) objects using noninvasive and contact loss techniques. The principle is to project parallel fringes on an object and then to record the object at two viewing angles. With an appropriate treatment one can reconstruct the 3-D object even when it has no symmetry planes. The 3-D surface data are available immediately in digital form for computer visualization and for analysis software tools. The optical setup for recording the object, the data extraction and treatment, and the reconstruction of the object are reported and commented on. Application is proposed for reconstructive/cosmetic surgery, CAD, animation, and research.

Subject terms: *three-dimensional scanner; reconstructive and plastic surgery; three-dimensional visualization.*

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1 Introduction

With the use of computer-aided design, diagnostics, modeling, and manufacturing there is an increasing need for fast and accurate reconstruction of 3-D objects. Several types of 3-D scanners are available on the market,[1] but they are expensive and too sensitive for recording live objects. Our investigation is oriented toward making a low-cost, accurate, and instantaneous recording 3-D scanner, with no need to "freeze" the subject. The 3-D surface data should be usable by a large number of computer platforms. In fact, the surface data are transformed into a set of points with x, y, z coordinates in ASCII format, readable by most currently available visualization and analysis software.

2 Optical Setup and 3-D Object Recording

To record the 3-D object, the following setup was used. Parallel fringes produced by a slides projector are projected onto the object as demonstrated in Fig. 1(a). Two recording devices are located at viewing angles α and β from the optical axis; see Fig. 1(b). At least two pictures of the object are recorded at the same time, the first picture at the viewing angle α and the second one at the viewing angle β. Examples of such pictures are shown in Fig. 2(a) and 2(b).

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The viewing angles, the fringe intensity, and the fringe resolution (number of fringes per millimeter) are controlled by the user.

3 Data Extraction and Processing

The pictures displayed in Fig. 2(a) and 2(b) are loaded in TIFF format into a digitalization program to extract the x, y, and z coordinates. The z coordinate is the number of fringes: $z=0$, s, $2s$, $3s$, ... is on the right side with the recording angle α, and $z=0$, $-s$, $-2s$, $-3s$, ... is on the left side, with the recording angle β, where s is the distance between two fringes. The fringe $z=0$ is the common fringe for both pictures. Every point in the picture is determined with its x, y, and z coordinates. Also, for each fringe $z=\text{constant}$, one has a set of coordinates x, y. The fringes ($z=\text{constant}$) represent planes known as splines. Consequently, the picture data are collected in a set of points in the following format:

- Recording angle α: set of 3-D coordinates x_α, y_α, z_α
- Recording angle β: set of 3-D coordinates x_β, y_β, z_β.

Also, the 2-D pictures are transformed into a set of 3-D coordinates. More details on the data extraction algorithms are reported in Ref. 2.

The axis system for measuring the 3-D space uses Cartesian coordinates. The two pictures recorded at the viewing angles α (right of the subject) and β (left of the subject) are transformed in the following way:

$$x=x' \cos\alpha + z' \sin\beta \ , \tag{1}$$

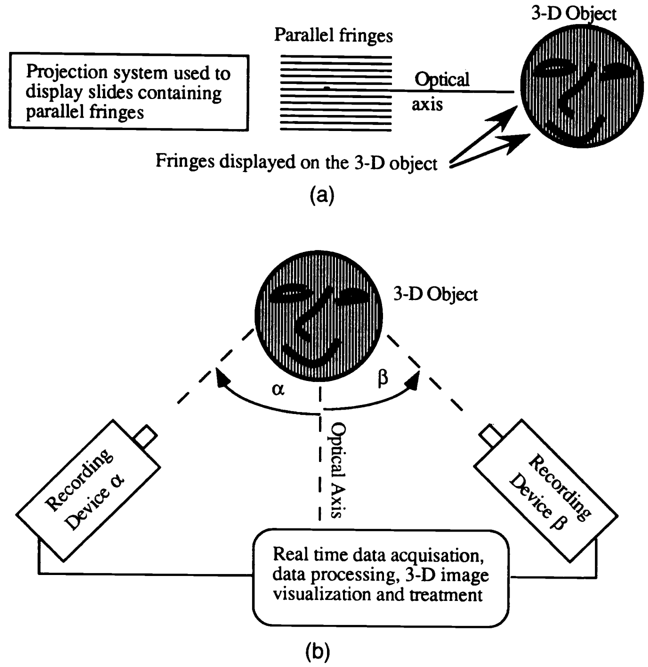


Fig. 1 (a) Optical setup used to display parallel fringes on a 3-D object. (b) Recording of the 3-D object.

$$z=-x' \sin\alpha + z' \cos\beta \ , \qquad (2)$$

$$y=y' \ , \qquad (3)$$

where x', y, y' are measured on the image, and $z=z'$ is the fringe number. From Eq. (2),

$$z'=\frac{z+x' \sin\alpha}{\cos\alpha} \ . \qquad (4)$$

Introducing Eq. (4) into Eq. (1), we have

$$x=x' \cos\alpha + \frac{\sin\alpha}{\cos\alpha}(z+x' \sin\alpha) \ . \qquad (5)$$

The set of points x, y, z are used. For example, in the case $\alpha=45$ deg ($\cos\alpha=\sin\alpha=0.707$), Eq. (5) becomes

$$x=z+1.41x' \ . \qquad (6)$$

The set of 3-D points has the coordinates x, y', and z' with x calculated from Eq. (6) and y' and z' measured on the image.

A similar transformation should be used for the part of the image that was recorded at the viewing angle β; then the two data sets (at angles α and β) are assembled together. The file containing the 3-D coordinates x, y', z' is used as input to the 3-D software; see Fig. 3(a). Data in such a format are easy to process and to interface with CAD/CAM or graphics programs.

4 Results

After reconstruction, the digitized 3-D object can be rendered and visualized in different modes such as point, wire frame, or solid mode with different material, lighting, triangulation, and interpolation. In this section we display some 3-D object reconstructions based on the above-described techniques.

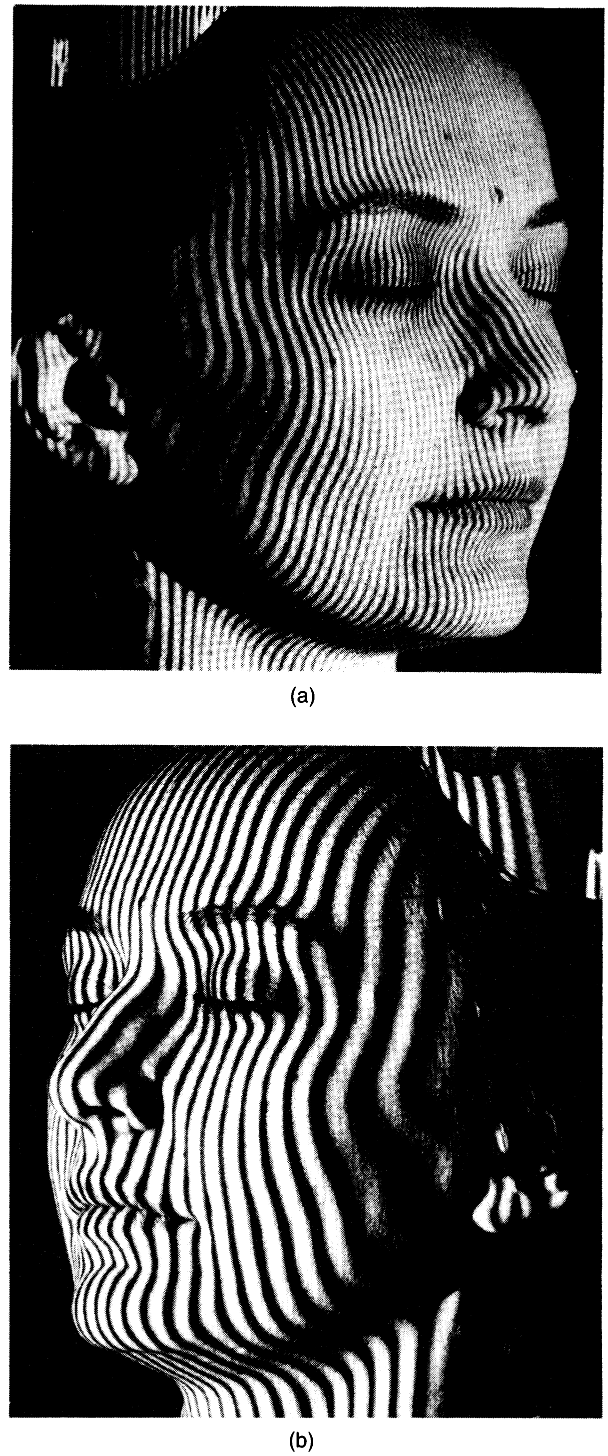
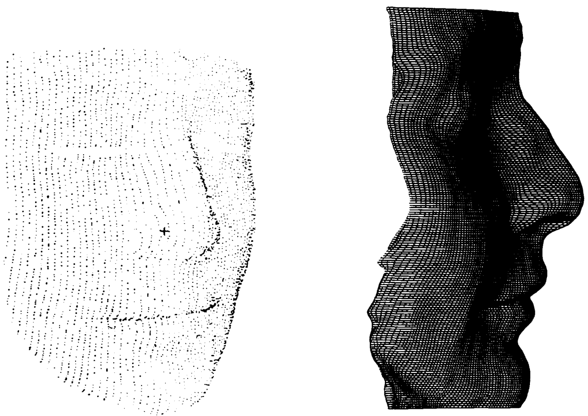


Fig. 2 Optical fringes projected on a woman's face: (a) viewing angle α is 45 deg, resolution 1 line/mm; (b) viewing angle β is -45 deg, resolution 0.5 line/mm.

Starting from the 3-D data, we may plot mode points, as displayed in Fig. 3(a). Delauney's triangulation and various methods of interpolation have been developed to produce wire frame models as shown in Fig. 3(b).



(a) (b)

Fig. 3 Reconstructed face in 3-D: (a) mode points, (b) wire-frame mode.

The software for this 3-D scanner was developed on a Silicon Graphics workstation, and it is based on the Iris Explorer visualization package.

5 Conclusion

Certain operations such as cutting slices, taking samples of surfaces, and drawing contour lines, details, and shapes of the reconstructed 3-D object are available. In this section we report some shapes, slices and details of the woman's face. Slices and shapes as displayed in Fig. 4(a), 4(b), and 4(c) contain valuable information, such as deformation or volume values, for use by reconstructive/cosmetic surgeons.

This 3-D scanner has principally been used to study nasal forms, but it has a wide application for studying other body surfaces and for the examination of breast surgery procedures. In general it is a helpful tool for CAD/CAM and product designers.

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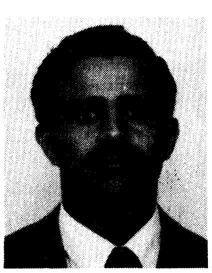
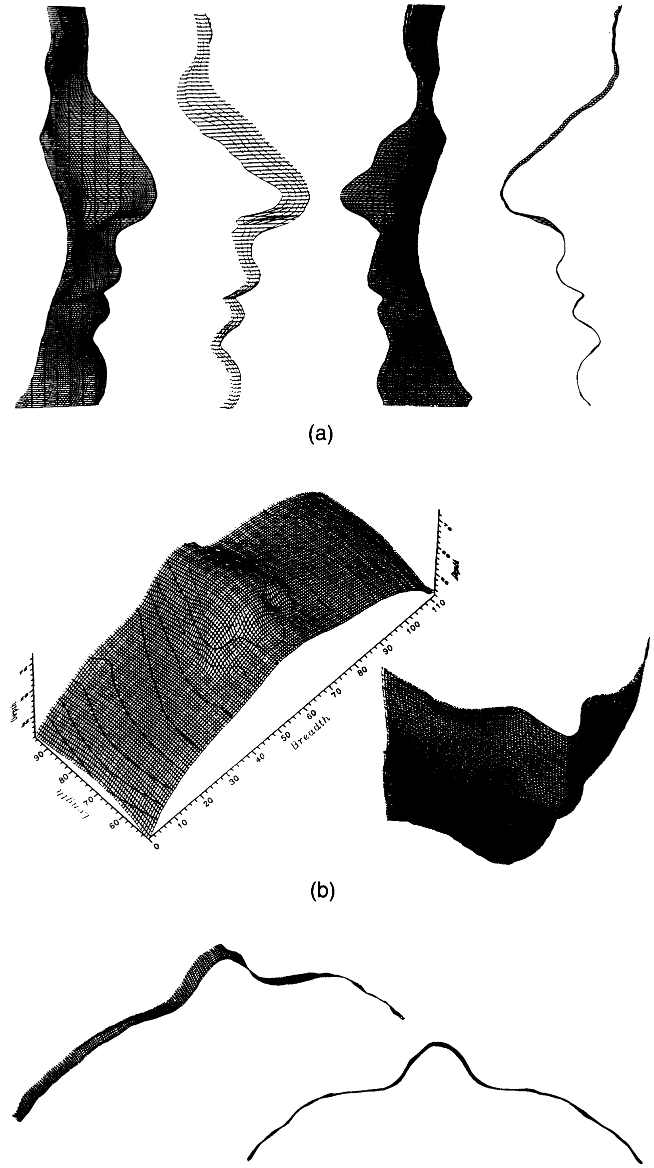


Taoufik Nouri received a diploma in electronics/physics and the degree of Doctor ès Sciences (PhD) from the University of Neuchatel, Switzerland, in 1986 and 1991, respectively. His thesis work was on knowledge-based optical system design and artificial intelligence. He is the author or a coauthor of many patents and publications in the field of optical system for medical and industrial applications. His current research interests include knowledge-based systems, optical system design, optical computing, fuzzy logic, artificial intelligence, and software engineering. He is a member of SPIE and ACM.



(a)

(b)

(c)

Fig. 4 (a) Vertical slices and sections through the woman's face. (b) Horizontal slices and sections through the woman's face. (c) Slice 5 mm thick and a section through the woman's face.