3-D Surface Characterization Using a Structured Light Technique

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***Resumo* – Descreve-se um sistema de aquisição tridimensional que usa uma técnica de luz estruturada, baseada na rápida projecção de uma sequência de padrões de luz, sobre a cena em análise. Este sistema tem múltiplas aplicações, nomeadamente, em antropometria. A sua primeira aplicação será a estimação do volume da mama, tendo em vista o dimensionamento de próteses e estudos relativos ao cancro da mama.**

***Abstract* – A three-dimensional data acquisition system, using a structured-light technique, based on the fast projection of a sequence of patterns on the scene under analysis, is described. This system has multiple applications, namely, in anthropometry. Its first application will be the estimation of woman breast volume, aiming at the sizing of prosthesis and breast cancer related studies.**

I. INTRODUCTION

Medical imaging techniques, such as magnetic resonance imaging and computed tomography, have been widely used for acquiring the three-dimensional (3-D) internal structure of the human body. However, there are many important biomedical applications requiring inexpensive, rapid, accurate, non-contact and safe measurement of human body external surfaces. Several examples of such applications can be given. In orthopaedics, the measurement of human trunk shape is very important for the detection of deformations of the spinal column. In plastic surgery, the accurate measurement of surfaces can assist surgeons to plan and evaluate changes before and after the surgery. In the therapy of burn injuries, burn area measurement is important for computing fluid replacement and the doses of therapeutic agents to be administered to the patient. In breast cancer treatment, the dimensioning of prosthesis, after a mastectomy, requires 3-D information about the breast, such as volume and shape.

The work described in this paper is the development of an accurate and non-contact measurement system for the 3-D measurement of human body surfaces, using a structured light technique. The main components of the system, the principle of the method, as well as the main steps of the procedures for the calibration and acquisition of 3-D data, are described. The performance of the system is evaluated and some preliminary results about its first medical application, the measurement of the breast of women that are subject to cancer treatment, are also presented.

II. 3-D MEASUREMENT OF HUMAN BODY SURFACES

Three main approaches have been used for measuring the 3-D shape of human body surfaces: methods by contact, stereophotogrammetry and structured lighting.

Several methods by contact have been used: water displacement and different special devices that are adapted to the object under measurement, such as a plastic cone, sometimes used for rough estimation of woman breast volume. Methods by contact, as the name implies, require contacting, and sometimes depressing, the skin. This is not convenient for two main reasons: it is not biologically safe, because it can carry a high risk of infection, as it happens with burn area measurement, and it may deform the surface, producing measurement errors. Moreover, data acquisition can be very time consuming and not comfortable to the person under measurement.

Non-contact techniques usually involve some form of stereo acquisition. Stereo is the process of inferring depth, or other geometrical information, about the surface of 3-D objects, using two or more images, acquired from different viewpoints. The procedure by which the 3-D location of an object point can be obtained, from two images, as the intersection of known lines of sight, is named triangulation.

Stereophotogrammetric techniques used in the past generally involved taking a pair of stereo photos of a human subject whose skin was first marked with a set of anatomical points. The photos, taken by a stereo pair of cameras, were then processed on an analytic stereo-plotter, to generate the 3-D information on the surface [1]. This technique was capable of producing accurate measurement of the human body surface, allowing the positioning of the predetermined anatomical points. However, it had two main drawbacks: the cost of the equipment and the difficulties in establishing correspondence between the pair of photos. Presently, computer based systems, like that described in [2], avoid the need of manually marking the set of anatomical points and establishing the correspondence between the points in the acquired images. In order to create some features on the surface, a light pattern is projected on it, and the correspondence between the two images, acquired with separate cameras, is established automatically, using image processing techniques.

In structured light techniques one of the cameras is replaced by a light source that projects known patterns onto the scene. Images of the known patterns are recorded using a single camera. By locating the image features of the light patterns and matching them correctly to the projected patterns, the three-dimensional positions of the points on the object surface can be determined by triangulation. Various forms of structured light may be projected onto a scene: points, lines (single, parallel or crossed) or more complex patterns. The use of a single point/line demands the scanning of the object and a corresponding image acquisition for each position of the projected point/line. By projecting more complex patterns onto the scene, range measurements can be performed from a single image of the scene, but a correspondence problem, between points of the projected pattern and of the acquired image, has to be solved. Space encoding has been proposed for solving this correspondence problem by projecting a sequence of coded binary patterns [3].

Many applications of non-contact human body measurement make use of biologically safe structured light. Several applications have been described: the measurement of human trunk shape for detection of deformations of the spinal column [4], the measurement of the human body size and surface shape for garment manufacturing [5], the quantitative assessment of the facial changes possible with and resulting from facial plastic surgery [6] and the measurement of the breast volume of lactating mothers [7].

In the following sections we describe the system developed, using a structured light technique, based on space encoding.

III. The 3-D acquisition system

The main components of the system hardware are: a personal computer; a structured light projection system, composed by a common slide projector, equipped with a computer controlled liquid crystal panel; and an image acquisition system, constituted by a TV camera and an image acquisition board.

The acquisition of 3-D information is based on the following structured light technique [3][8]. A set of parallel lines, alternately transparent and opaque, are generated on the liquid crystal panel, originating a pattern of light and shadow lines on the scene under analysis. The 3-D coordinates of a scene point are obtained by intersecting the plane of light/shadow that illuminates the point with its line of sight, determined by the camera (figure 1). For that purpose, it is necessary to identify unambiguously each of the light/shadow planes. This is achieved by assigning a numerical code to each plane and illuminating the scene with additional light patterns, in such a way that allows the recovery of the code, from a set of acquired images.

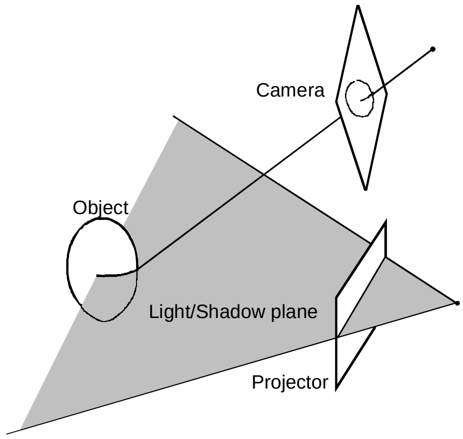


Figure 1 – Principle of the 3-D data acquisition method.

The scene is illuminated with 128 light planes and 128 alternating shadow planes. A numerical code, from 0 to 255, is assigned to each light/shadow plane. The set of projected patterns corresponds to the bit planes of the binary representation of these codes. The number of bit planes is 8, which is the number of bits needed to represent the 256 codes. The initial pattern, corresponding to the least significant bit plane (bit plane 0), is made of alternate transparent and opaque lines, as referred above; the pattern corresponding to the next significant bit plane (bit plane 1) is made of alternate pairs of transparent and opaque lines, and so on (figure 2). Finally, bit plane 7 is made of 128 consecutive transparent lines and 128 consecutive opaque lines (figure 3). From the sequence of light intensities measured at a point of the scene, when it is illuminated by the sequence of projected patterns, it is possible to recover the code of the corresponding light/shadow plane (figures 2 and 3). In order to obtain the equation of the plane, from its code, as well as the equation of the line of sight of the point, from its pixel coordinates, it is necessary to make a geometrical calibration of the system.

IV. Calibration procedures

The calibration of the system consists of two main steps:

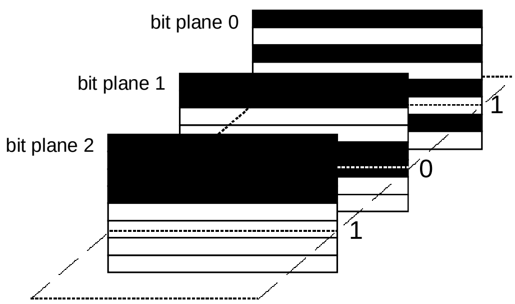


Figure 2 – Illustration of projected patterns for 8 light/shadow planes. The code of the shown light plane is 101_2.

camera calibration and projector calibration. The order of the calibration steps is important, as the results of the calibration of the camera are needed for projector calibration [10]. Camera calibration is the process of calculating the parameters that allow the determination of the line of sight associated with each pixel of an image acquired with the camera, given the coordinates (i, j) of that pixel. Projector calibration is the calculation of the parameters that allow the determination of the equation of each light/shadow plane, given its code.

The model used for the camera is the DLT (Direct Linear Transformation) [9], according to which the transformation of a point in 3-D space, (x,y,z), into a point of the acquired image, (i,j), represented in homogeneous coordinates, is given by

$$\begin{bmatrix} \mathrm{w}i \\ \mathrm{w}j \\ \mathrm{w} \end{bmatrix} = \begin{bmatrix} C_1 & C_2 & C_3 & C_4 \\ C_5 & C_6 & C_7 & C_8 \\ C_9 & C_{10} & C_{11} & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \qquad \text{(eq. 1)}$$

or

$$i = (C_1 \cdot x + C_2 \cdot y + C_3 \cdot z + C_4) \,/\, (C_9 \cdot x + C_{10} \cdot y + C_{11} \cdot z + 1)$$
$$j = (C_5 \cdot x + C_6 \cdot y + C_7 \cdot z + C_8) \,/\, (C_9 \cdot x + C_{10} \cdot y + C_{11} \cdot z + 1) \qquad \text{(eq. 2)}$$

where the C_i's are the calibration parameters to be calculated. These parameters reflect the relationship between the object-space reference frame and the image-plane reference frame. It should be noted that equation 2 can be rewritten as

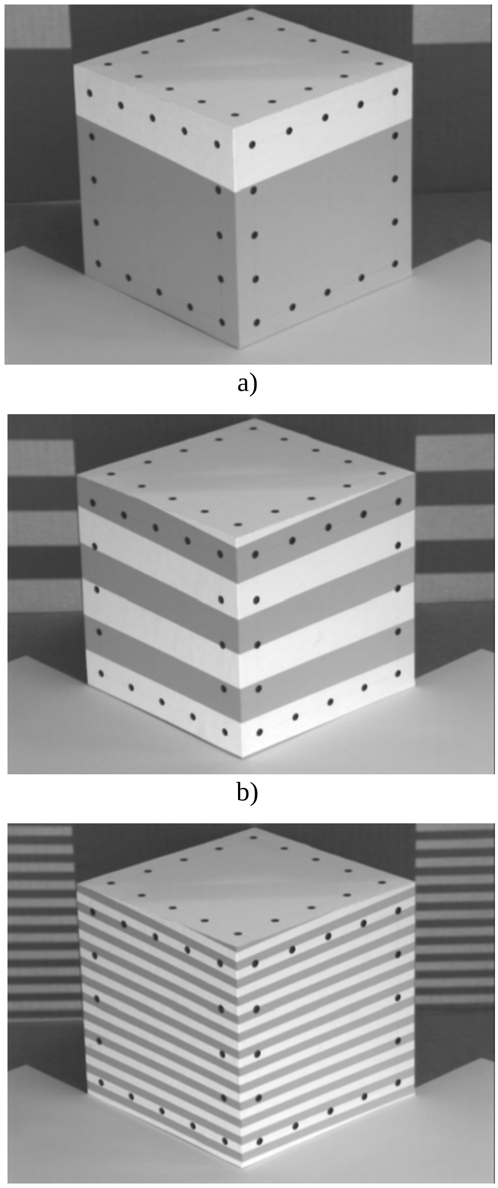
$$(C_1 - C_9 \cdot i) \cdot x + (C_2 - C_{10} \cdot i) \cdot y + (C_3 - C_{11} \cdot i) \cdot z = i - C_4$$
$$(C_5 - C_9 \cdot j) \cdot x + (C_6 - C_{10} \cdot j) \cdot y + (C_7 - C_{11} \cdot j) \cdot z = j - C_8 \qquad \text{(eq. 3)}$$

that represents a line in 3-D space (the intersection of two planes), which is the line of sight associated with pixel (i,j).

The camera calibration procedure consists of the following main steps:

- To acquire an image of a cube, on the visible faces of which 48 circles, whose coordinates are known with great accuracy, are marked.
- To detect these circles on the image, by applying three different thresholds (one for each face of the cube), and calculate the pixel coordinates of their centroids.
- To establish the correspondence between the circles on the cube and on the image and build system of equations 1, by replacing the coordinates, (x,y,z) and (i,j), of the corresponding centroids.
- Finally, solve the system of equations, obtained for all the pairs of points, for the C_i's, using a least-squares method.

Although, 6 non-coplanar object points would be enough to obtain the camera parameters, much more points are used, in order to reduce the influence of possible small errors in image formation and processing. To improve the accuracy of the calibration, the calibration points must be spread uniformly over all the measurement volume.



a) b) c)

Figure 3 – Acquired images of the calibration cube corresponding to a) bit plane 7, b) bit plane 4 and c) bit plane 2, for 256 light/shadow planes.

The model used for the projector is similar to that used for the camera. The relationship between the code of a light/shadow plane, p, and the 3-D coordinates of the points of the scene, (x,y,z), through which it passes, is given by [10]:

$$\begin{bmatrix} \mathrm{w}p \\ \mathrm{w} \end{bmatrix} = \begin{bmatrix} P_1 & P_2 & P_3 & P_4 \\ P_5 & P_6 & P_7 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \qquad \text{(eq. 4)}$$

or

$$p = (P_1 \cdot x + P_2 \cdot y + P_3 \cdot z + P_4) \,/\, (P_5 \cdot x + P_6 \cdot y + P_7 \cdot z + 1) \qquad \text{(eq. 5)}$$

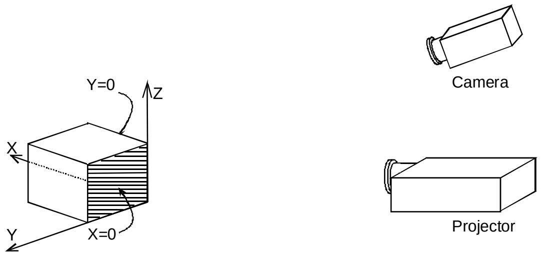


Figure 4 – Projector calibration.

where the P_i's are the calibration parameters to be calculated.

In this case, only one equation is needed to establish the relationship between 3-D coordinates and the code of a light/shadow plane, *p;* this code is equivalent to the "*j*-coordinate" of the projected lines, drawn on the image plane of the projector.

Equation 5 can be rewritten as

$$(P_1 - P_5 \cdot p)\cdot x + (P_2 - P_6 \cdot p)\cdot y + (P_3 - P_7 \cdot p)\cdot z = p - P_4 \qquad \text{(eq. 6)}$$

that is the equation of the projected light/shadow plane whose code is *p*.

The calibration procedure for the projector is:

- To project the pattern sequence, referred in section III, on the calibration cube (figures 3 and 4).
- To determine, on the image corresponding to bit plane 0, the central pixels of the projected lines. Taking into account the relative position and orientation of the camera and the projector, the projected lines are predominantly horizontal. So, the central pixels are obtained by analysis of the intensity profiles of the columns of the image: first, the local maxima (peaks) and minima (valleys) of the profile are determined, using some heurist rules to distinguish valid peaks and valleys from those caused by electronic noise [8]; then, the position of the central pixels is calculated as the centroid of the area of the intensity profile delimited by two consecutive peaks or two consecutive valleys. The points of the object whose 3-D coordinates will be calculated are those corresponding to the central pixels.
- To calculate the 3-D coordinates of these points, by intersecting the line of sight of each pixel, calculated using the results of the camera calibration, with the faces of the cube, whose equations are respectively x=0 and y=0, taking into account the chosen 3-D reference frame (figure 4).
- For each pair, (x,y,z) and p, build equation 2.
- Finally, solve the obtained system of equations for the P_i's, using a least-squares method.

The models used for the camera and the projector, as well as the calibration procedures and several image processing steps, are detailed in [10].

V. Data acquisition

After the system is calibrated, it is possible to acquire 3-D data. For this, the cube, used to calibrate the system, must be replaced by the object to be measured, and the settings of the camera and the projector, namely, their position, orientation and focal distance, must keep the values established during calibration. The acquisition phase consists of the following main actions, also detailed in [10]:

- To project the sequence of patterns, referred before, on the object to be measured, and to acquire a set of images, one image for each projected pattern. In addition to the 8 bit plane images, an image is acquired with only ambient light. This image is subtracted to each of the other images, in order to remove the ambient light component that could perturb the location of the central pixels of the projected lines. A similar subtraction is done during the calibration phase.
- To determine, on the image corresponding to bit plane 0, the central pixels of the projected lines. As it was said in the previous section, these pixels are obtained by analysis of the intensity profiles of the columns of the image.
- To determine the code associated with each of the projected lines. This is done in the following way: the intensity of the central pixels of the projected lines, in bit plane *i* image, is compared with a local threshold; if the intensity is greater than the calculated threshold then the *i*-th bit of the code is 1, otherwise it is 0. The local threshold is calculated, in the bit plane 0 image, as the mean value of the intensities of the closest (to the central pixel under analysis) peak and valley, in the intensity profile of the column to which the pixel belongs. The 8 bits of the code are obtained by applying this procedure to each of the images, corresponding to the 8 bit planes.
- To determine, for each of the central pixels: 1) the equation of the line of sight associated with it, using its coordinates (i, j) and the parameters resulting from the calibration of the camera (eq. 3); 2) the equation of the light/ shadow plane that illuminates the corresponding point of the object, using the code of the plane and the parameters resulting from the calibration of the projector (eq. 6).
- To intersect the above-referred line of sight and plane, in order to obtain the 3-D coordinates of the corresponding point of the object. This is achieved by solving, for (x,y,z), the following system of equations, resulting from equations 3 and 6:

$$(C_1-C_9\cdot i)\cdot x+(C_2-C_{10}\cdot i)\cdot y+(C_3-C_{11}\cdot i)\cdot z=i-C_4$$
$$(C_5-C_9\cdot j)\cdot x+(C_6-C_{10}\cdot j)\cdot y+(C_7-C_{11}\cdot j)\cdot z=j-C_8$$
$$(P_1-P_5\cdot p)\cdot x+(P_2-P_6\cdot p)\cdot y+(P_3-P_7\cdot p)\cdot z=p-P_4$$
(eq. 7)

The last two steps must be repeated for each of the central pixels of the projected lines; these are the points for which it is possible to obtain the 3-D coordinates. Although it is not possible to obtain the 3-D coordinates for all the points of an intensity image, it is possible to obtain a rather dense set of 3-D points of the object under analysis (more than 50000 points can be easily obtained).

VI. System implementation and evaluation

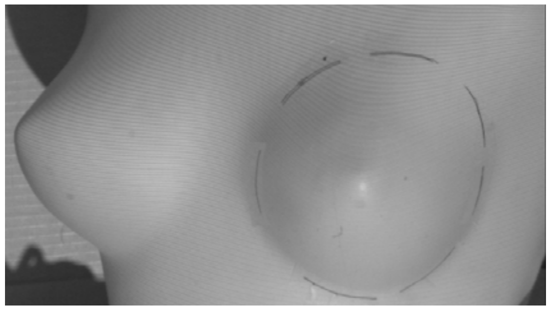
The system was built using the following main components: a 166 MHz Pentium based PC, a CCD camera, equipped with a 12.5-75 mm zoom lens, an image acquisition board, and a common slide projector, adapted in order to accommodate the liquid crystal panel, in the place of the slide, used to generate the projected patterns under computer control. The relative position and orientation of the camera and the projector are those depicted in figures 1 and 4; the projector is placed horizontally and the camera is placed above the projector. The acquired images have a spatial resolution of 768×572 pixels, with 8 bits/pixel. The software has been developed in Visual C++.

Different measurement volumes and resolutions are obtained with this system, by adjusting the zoom factors of the camera and the projector, and their distance to the object. However, taking into account that the number of projected light/shadow planes is fixed, the 3-D spatial resolution decreases as the measurement volume increases.

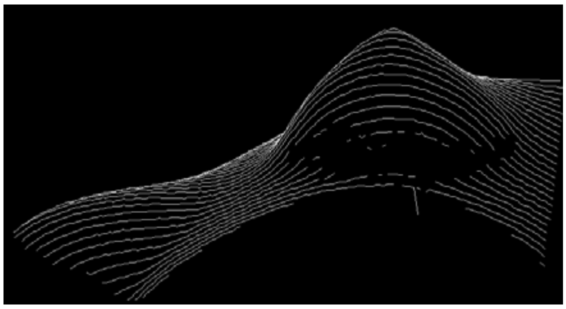
The system was evaluated under two main points of view: the accuracy of the acquired 3-D data and the acquisition time for the set of intensity images that are necessary to obtain that 3-D data. This time is about 0,95 seconds. It is extremely important that it is short, mainly in anthropometrical applications, since it is necessary that the patient keeps static during image acquisition. Another time, that is not so critical, is the computation time for the 3-D coordinates; this is about 0,81 ms/point.

The accuracy of the system was evaluated in the following way: a cube, whose dimensions are known with an accuracy of ±0.05 mm, was placed at about 1 meter from the camera and the projector; the coordinates of points of the visible faces of a cube were determined; the measurement error was evaluated as the mean distance of the measured points to the corresponding faces. This distance, evaluated over several experiences, was always less than 0,3 millimeters. Its typical value was about 0,15 millimeters, when the optical axes of the camera and the projector were making an angle of about 30°, and 0,26 millimeters when that angle was about 15°.

The interface of the system makes possible that anyone, even a non-expert, be able to calibrate the system and acquire 3-D data. The procedures presently included in the



a)



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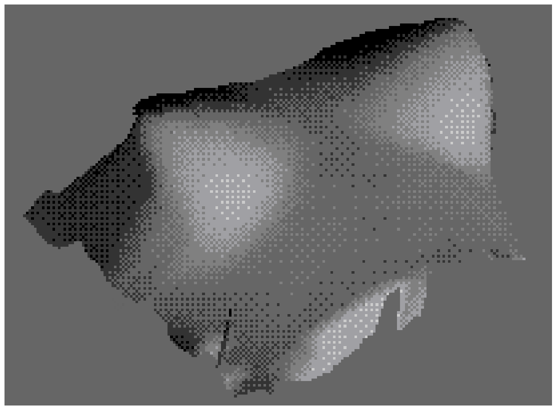

c)

Figure 5 – a) Polyester breast used in preliminary experiments; b) wireframe and c) shaded representation of acquired 3-D data.

system, allow the 3-D visualization of the acquired data from a chosen point of view [10] [11] (figure 5), the processing of the data in order to obtain information about the measured objects, such as volumes and profiles, and the saving of the processing results into a database.

VII. Medical applications of the system

The first medical application of this system will be the measurement of breast volume and shape. A project[1], resulting from the collaboration between INEB and IPO (Porto), is presently under development. The main objective of this project is to build a system that can be used for breast volume measurements. It is expected that this system can be used not only for the sizing (determination of

[1] This project has been funded by FCT (Fundação para a Ciência e Tecnologia), under contract PBIC/C/TIT/2456/95

the volume and shape) of breast prosthesis but also for the quantification of drugs to be administered to the patients when the option for a conservative surgery is taken.

In order to obtain the volume of the breast it is necessary to choose a base or reference surface that together with the exterior surface of the breast delimits its volume. That reference surface is obtained by fitting a plane to a set of points on the thorax of the patient. These points are selected interactively by the user. The volume of the breast is obtained by numerical integration: the points on the surface of the breast, whose coordinates have been determined, are grouped, forming adjacent triangles (figure 6); the vertices of these triangles are projected on the reference plane and the volume of the prismatic elements thus obtained is summed, to obtain the total volume.

The profile of the breast along a chosen line can also be obtained.

Two difficulties have arisen in the first experiments made with real women breasts (figure 7). The first difficulty is that, in some cases, a small portion of the breast is occluded. This problem can be minimized if the patient raises her arms, during image acquisition; we plan to introduce a second camera-projector pair, taking another view, from a different angle, to solve this problem [7]. The second difficulty is the choice, in the acquired images, of the points to be used for fitting the reference plane. For the moment, this difficulty was solved by using a plane card with a hole, which is held against the thorax of the patient, by the physician, as shown in figure 7.

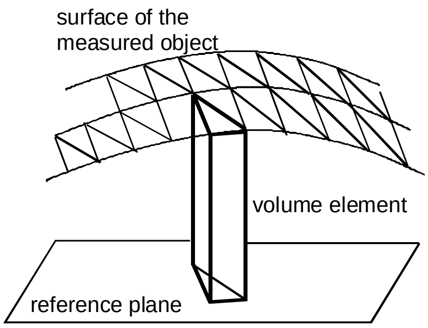

Figure 6 – Volume calculation, using a reference plane.

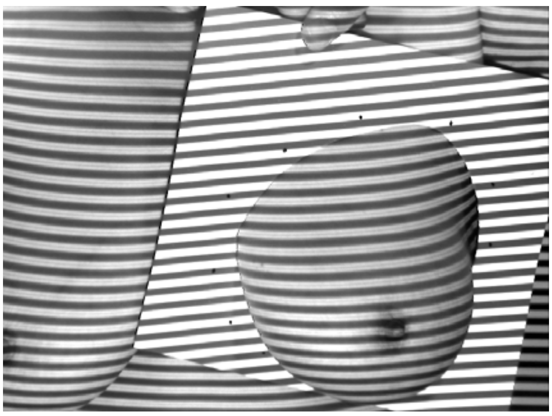

Figure 7 – Measurement of a real woman breast.

Other possible medical applications of this system are being considered, namely, in the orthopaedics field.

VIII. CONCLUSION

A low cost, non-contact 3-D data acquisition system, based on a structured light technique, which will be used in anthropometrical applications, has been described. The components of the system, the principle of method, the calibration and data acquisition procedures, as well as some performance results, have been presented. The accuracy of the system is very good and the acquisition time is short enough to allow its application in anthropometry.

The first application of this system will be in the cancer treatment field, for the determination of volumes and profiles of breasts of women that suffer from cancer. The accurate quantification of the volume of the breast can contribute significantly to the progress of clinical investigation and practice. The quantification of the ratio between the volume of the tumor (that can be obtained, for example, by echographic means) and the volume of the breast will make possible a more safely option between conservative and radical surgery, taking into account that the evaluation of the size of the breast is, at the present, essentially qualitative (great, medium, small). This quantification will allow a more objective comparison among results obtained through the application of different treatments. Besides, when the option for mastectomy is taken, the determination of the volume and the area of implantation of the extracted breast, before the operation, or of the remaining breast, will make possible the correct sizing of the prosthesis. Some experiments with patients have already been made and other will be made soon. The results of the first experiments seem promising and the physicians involved in this project consider that this system will be a great help for clinical practice and research.

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