

AUTOMATED THREE-DIMENSIONAL MEASUREMENT USING MULTIPLE ONE-DIMENSIONAL SOLID-STATE IMAGE SENSORS AND LASER SPOT SCANNERS

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ABSTRACT

A multi-station photogrammetric approach to shape measurement of three dimensional (3-D) objects is discussed which utilizes laser beams to scan the visual field of interest and cylindrical lenses and one-dimensional image sensors to detect the perspective position of a light spot in the field. The perspective position of the spot is measured by three or more one-dimensional image sensors each of which is set orthogonal to the axis of the cylindrical lens. The combined use of them leads to automated high-speed computation of shape of objects since the position of the spot in $n \times n \times n$ pixels of a 3-D visual field can be determined only by measuring $n+n+n$ photocells of three one-dimensional image sensors located at a suitable perspective. The 3-D image of the object is computed using a method based on triangulation. Results of measurement as well as image processing for human torso are given.

INTRODUCTION

An important class of stereometric measurement deals directly with range information in order to determine the three dimensional (3-D) shape of objects in the measurement field (Jarvis, 1983). The two most popular range measuring methods are based on triangulation and time-of-flight. The time-of-flight method determines the range from the time needed for the light or the ultrasound to travel from the transmitter to the target and the phase shift rather than travel time is measured to determine the range (e.g., Nitzan et al., 1977).

Triangulation can be subdivided into stereoscopic and projected light methods. The basic principles of stereo ranging are well known. The stereo pair of images, which can be obtained either from two cameras or from one camera in two positions, is analyzed to compute the range. However, it is difficult to compute the position of a point in one image because one must find the corresponding point in the other image. One way to avoid this difficulty is to use specially controlled illumination. A sheet of light from a slit projector, a laser beam diverged by a cylindrical lens, or a collimated light beam is projected on the object and the resulting image is recorded by means of a TV camera or a photo-diode image sensor (Oshima & Shirai, 1979; Hierholzer & Frobin, 1980; Carrihill & Hummel, 1985). Every point in the image determines a ray in space, and the space coordinates of the point hit by the ray can be determined by applying a simple trigonometric formula.

As a special case of a stereophotographic image, Moire topography has been widely utilized for mapping curved surfaces (Windischbauer, 1981). An advantage of using Moire techniques is that contour lines are produced in real time as a direct result of the physical process and a topograph can be produced by using simple and inexpensive equipment. However, Moire techniques may not be convenient for the purpose of analytically representing an entire surface because the contour lines are determined relatively, not absolutely, so that it is not easy to connect two or more topographs taken from different points of view.

Our spot scanning approach for biostereometric measurement utilizes a laser beam scanned by mirrors and three or more one-dimensional (1-D) cameras. The 1-D camera consists of the combined use of cylindrical lens and line sensor (Yamashita et al., 1982). The space coordinates of a laser spot on the object can be measured through multiple 1-D cameras. In this paper, the automatic acquisition system for stereomeasurements based on multiple 1-D cameras, an automated calibration scheme to estimate the camera parameters and an application for stereomeasurement of human body surface, will be described.

MULTIPLE 1-D CAMERA SYSTEM FOR STEREO METRICS

Figure 1 shows the basic geometrical arrangement of multiple 1-D cameras for stereometric measurement. The system has three functional components: a laser light source, an optical scanner and three 1-D cameras. The laser beam is scanned through the two-directional scanning mirror to cover the field of interest. The beam forms a marking spot on the surface of observed objects, and a portion of the reflected light is captured by each 1-D camera. As illustrated in Fig. 2, the 1-D camera consists of the combined use of cylindrical lens and linear image sensor. A cylindrical lens makes a line focus and, therefore, the image of the light spot is projected onto a line parallel to the nodal axis of the cylindrical lens. The position of the line focus can be measured by a 1-D image sensor orientated orthogonally. The position of the illuminated photocell

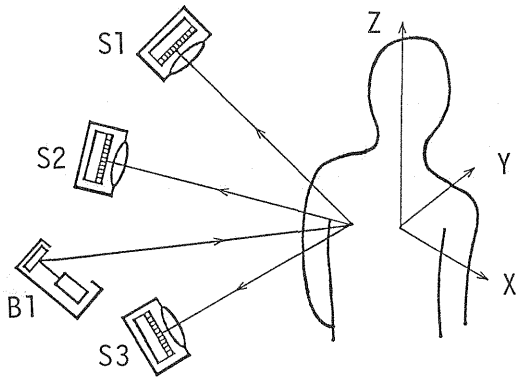


Fig. 1. Geometrical arrangement of multiple 1-D cameras (S1-S3) and a light source with two-directional scanner (B1).

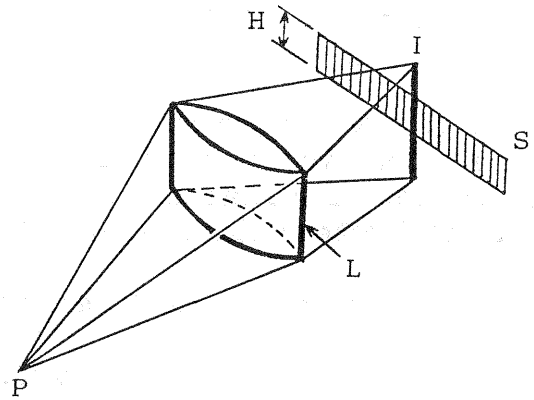


Fig. 2. 1-D camera which consists of the combined use of a cylindrical lens (L) and a linear image sensor (S).

of the sensor identifies a plane lying along the nodal axis of the lens containing the light spot. A suitable spatial arrangement of three 1-D cameras localizes the light spot in the 3-D object space through the intersection of the three independent planes.

A significant advantage of this system is that the coordinates of a light spot in the three dimensional space can be measured without image analysis as well as automatically at high speed. The reason for this is that the coordinates of a light spot within $n \times n \times n$ pixels of a 3-D object space can be determined only by simultaneously measuring the projected position of the spot within $n+n+n$ photocells of three 1-D cameras located at a suitable perspective. Thus, the object coordinates of a light spot can be determined by means of such simple equipment, making possible an analytical representation of three dimensional shape of objects.

MATHEMATICAL FORMULATION OF THE MEASUREMENT SYSTEM

The object coordinate system, in which observed objects are to be reconstructed, is defined arbitrarily as a simple right-hand Cartesian system but fixed in the measurement field (see Fig. 1). In imagery by convergent projections, all incident light rays are assumed to intersect at a common point on the optical axis, which is called the perspective centre Q with image coordinates (s_0, f) . Under close-range circumstances like biostereometrics, f will become slightly larger than the focal length of the lens. The perspective centre Q may be referred to the camera station (position) when it is described with respect to object coordinates $q(q_x, q_y, q_z)$. The projective equation existing between the coordinates $p(x, y, z)$ of an object point P, of its image $S(s, 0)$ and of the camera station Q is

$$\frac{(\mathbf{p}-\mathbf{q}) \cdot \mathbf{w}}{s-s_0} = \frac{(\mathbf{p}-\mathbf{q}) \cdot \mathbf{u}}{f} = k \quad (1)$$

where k is a proportionality factor and a boldface lower case letter indicates a column vector and \cdot represents the inner product of two vectors. Here, the camera orientation vectors \mathbf{u} and \mathbf{w} are described with respect to object coordinates which must satisfy

$$\mathbf{u} \cdot \mathbf{u} = \mathbf{w} \cdot \mathbf{w} = 1 \quad (\text{unit vector}), \quad (2)$$

$$\mathbf{u} \cdot \mathbf{w} = 0 \quad (\text{orthogonality}). \quad (3)$$

The various notations introduced until now are illustrated in Fig. 3. Thus, the projective equation formalizes that P , S and Q are on a common straight line. For M (three or more) 1-D cameras located around the object, if the orientation \mathbf{u}_i and \mathbf{w}_i , the camera station $\mathbf{q}_i (q_{xi}, q_{yi}, q_{zi})$ and the perspective centre $Q_i (s_{0i}, f_i)$ of each camera are known, the position of the illuminated photocell $s_i, i=1, 2, \dots, M$, will serve to reconstruct the location of a light spot P . In a laboratory the cameras can be fixed at a suitable perspective and these camera parameters are measured directly. However, in portable operation, as for example a medical application, it may be necessary to set up and disassemble the equipment per object to be measured, so rapid and automated calibration scheme is needed which a nonexpert can immediately use. In the following, an automated calibration procedure will be described in order to determine these parameters by observing a number of control points with known locations.

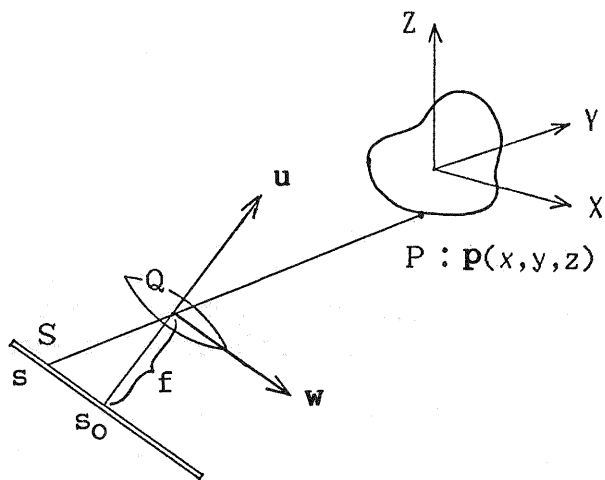


Fig. 3. Projective relation between object and image coordinates for the 1-D camera.

PROCEDURE FOR AUTOMATED CALIBRATION

For an automated calibration, a set of equations relating observations and unknown quantities must be obtained. Equation (1) can be written as

$$k \frac{s-s_0}{f} = \frac{\mathbf{p} \cdot \mathbf{w} - h}{\mathbf{p} \cdot \mathbf{u} - g} \quad (4)$$

where,

$$h = \mathbf{q} \cdot \mathbf{w}, \quad g = \mathbf{q} \cdot \mathbf{u} \quad (5)$$

By eliminating the proportionality factor k in (4) and defining

$$\mathbf{d} = (x, y, z, l, s_x, s_y, s_z)' \quad (6)$$

$$\mathbf{t} = (t_1, t_2, t_3, t_4, t_5, t_6, t_7)' \quad (7)$$

with

$$(t_1, t_2, t_3)' = (fw + s_0 u)/g, \quad (8.1)$$

$$t_4 = -s_0 - fh/g, \quad (8.2)$$

$$(t_5, t_6, t_7)' = -u/g, \quad (8.3)$$

we obtain

$$\mathbf{d}'\mathbf{t} = -s \quad (9)$$

where ' stands for a matrix or vector transpose. In order to determine the camera parameter, N control points with known locations must be provided. Let the object coordinate of the j th control point P_j be $P_j(x_j, y_j, z_j)$. Supposing that the 1-D camera being calibrated measures these N control points consecutively and then their image $S_j(s_j, 0)$ for the 1-D camera are obtained. Since each control point P_j must satisfy Eq. (9), the relation between P_j , S_j (known or observed quantities) and camera parameters \mathbf{t} (unknown) is described in a matrix form as follows:

$$\mathbf{D}\mathbf{t} = -\mathbf{s} \quad (10)$$

with

$$\mathbf{s} = (s_1, s_2, \dots, s_N)'. \quad (11)$$

Here, \mathbf{D} is an $N \times 7$ matrix each column of which consists of the vector \mathbf{d} , as defined in Eq. (6), for each control point. The least squares estimation procedure gives an estimate of the camera parameter vector \mathbf{t} from Eq. (10) as

$$\mathbf{t} = (\mathbf{D}'\mathbf{D})^{-1}\mathbf{D}'(-\mathbf{s}). \quad (12)$$

Note that Eq. (12) requires seven or more control points to estimate the camera parameter vector \mathbf{t} . If necessary, the optical parameters (s_0, f) as well as the geometrical parameters u, w, q of the 1-D camera can be uniquely determined from \mathbf{t} using Eqs. (2), (3), (5), (8.1), (8.2) and (8.3). Thus, the parameter vector \mathbf{t} of the 1-D camera is determined automatically from $N (>=7)$ control points with known object coordinates.

CALCULATION OF THE OBJECT COORDINATES OF A LIGHT SPOT

Even if only three perspective views given by three 1-D cameras are sufficient for space localization of a light spot which are visible to the three cameras, the rationale of using multiple cameras (three or more) is based on the fact that the resulting redundancy provides a greater working range as well as a reduction of uncertainty. Therefore, the shape measurement of 3-D object can be, in general, performed using multiple 1-D cameras set up around it.

When a light spot in the object space is observed by three or more 1-D cameras, the object coordinate of a light spot $p(x, y, z)$ must satisfy the 1-D perspective transformation with respect to each 1-D camera:

$$(t_{i1}+s_i t_{i5} \quad t_{i2}+s_i t_{i6} \quad t_{i3}+s_i t_{i7}) \begin{pmatrix} x \\ y \\ z \end{pmatrix} = -s_i - t_{i4} \quad (13)$$

where $(s_i, 0)$ represents the image coordinates measured by the i th 1-D camera and $t_i = (t_{i1}, t_{i2}, t_{i3}, t_{i4}, t_{i5}, t_{i6}, t_{i7})'$ is the parameter vector of i th camera determined by the calibration procedure stated above. For a multiple 1-D camera system, $p(x, y, z)$ can be estimated through the simultaneous equation of (13) for each 1-D camera, which results in finding the least squares solution.

SYSTEM CONFIGURATION FOR BIOSTEREOMETRICS

Figure 4 shows the major components in our biostereometric measurement system. A 1.5mW He-Ne laser beam is used to make a light spot on the object surface. The optical scanner drives the mirrors to sweep the beam in two directions over the whole area of interest. A cylindrical lens gathers a portion of the reflected light. The dimension of the cylindrical lens is 60mm in length and 50mm in width with the focal length is 47mm. As a line sensor, a MOS photodiode array (MN512KV, Matsushita Co.) is chosen because of its high sensitivity as well as low noise performance. The number of photodiodes is 512 and the pitch of the diode array is 0.028mm.

The video signal from each photodiode is read-out by series of clock pulses triggered by the start pulse and is passed through a differential amplifier followed by a peak holder before it is fed to a maximum-intensity detecting circuit. This circuit compares the output from all photodiodes and detects both the maximum value and the address of the photodiode which indicates the maximum value. The content of a 9-bit counter is latched when the comparator finds a greater intensity than before. Thus, after scanning all photodiodes, the address data is transferred to the computer. The maximum value of the intensity is utilized to adjust the focus in the stage of calibration. In the stereometric measurements, this maximum value is also digitized and is transferred to check whether the measured light spot is reflected from the object surface or from the background.

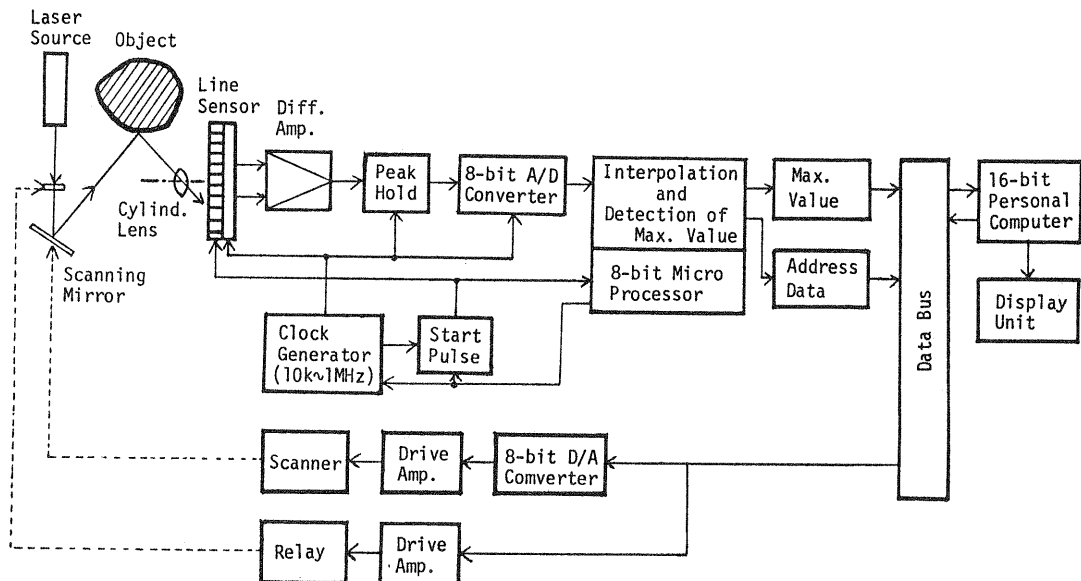


Fig. 4. Components of the multiple 1-D camera stereometric system.

The optical scanner is controlled by the computer through an 8-bit digital-analog converter. A stepwise scanning is desirable for a successful detection of the maximum intensity because the movement of a spot during measurement of the intensity distribution in a photodiode array may result in missing the address data. However, the stepwise scanning will require a higher performance in a high frequency range and a short step-response time.

All 3-D measurements by means of triangulation must make a trade off between accuracy and disparities between two different views. For accuracy, a large separation between each camera is desirable. However, as the separation increases, the disparities between different views also increases, which results in missing data because many points in the scene will be seen by one camera but not by the others. Our stereometric system was assembled to measure the shape of the torso surface of a standing or sitting subject. Four 1-D cameras and two two-directional optical scanners were used for a greater working range. Three of the four 1-D cameras were set in a horizontal plane at an angle of nearly 45 degrees and last one was in a vertical plane. The 1-D cameras were located at a distance of nearly 1.5m from the object in order to sense a light spot over a field of 0.5m*0.5m with a range resolution of c.a 1.5-2mm (0.3-0.4% in relative error).

RESULTS OF PRELIMINARY EXPERIMENTS

The position of the light spot is determined only by detecting a photo-cell which indicates the maximum output in the photo-diode array, providing that the form of intensity distribution of the array becomes unimodal. This is a simple and robust algorithm to detect the image coordinate. As

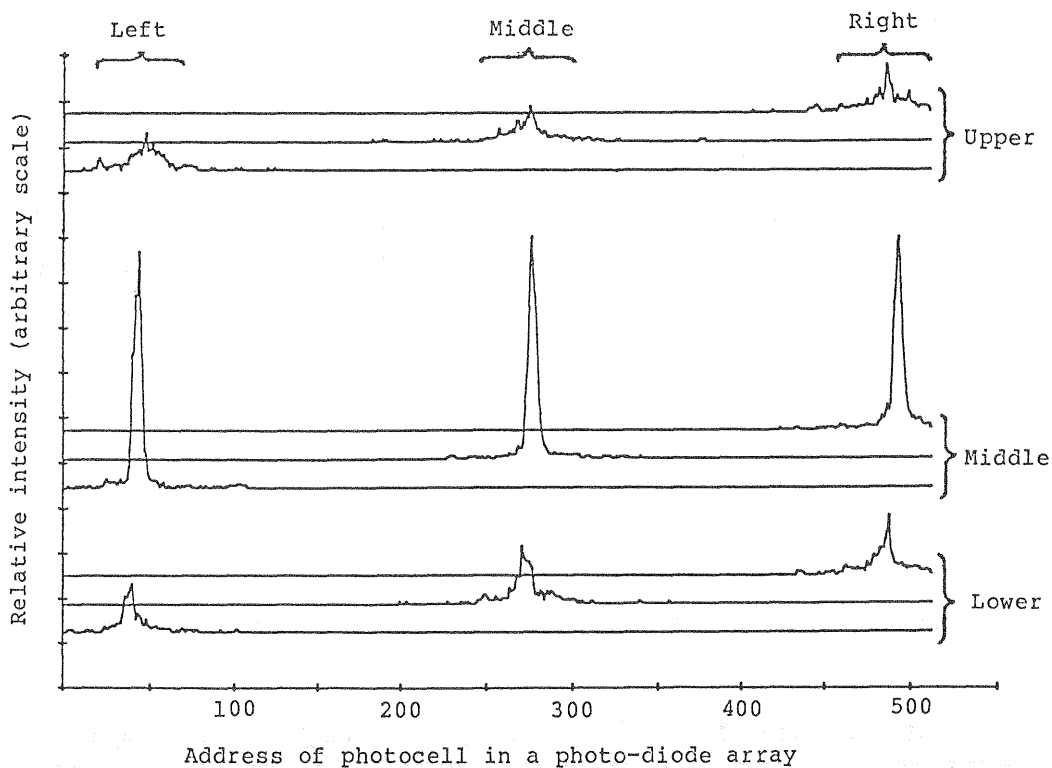


Fig. 5. Examples of the intensity distribution in a linear image sensor combined with a cylindrical lens.

saturation or multimodal distribution of the output can be expected to take place in real situations, more sophisticated algorithm to find the centre of intensity distribution should be developed for a wider dynamic range. Figure 5 shows typical forms of the intensity distribution of an 1-D camera when a light spot exists in different positions in the visual field. Since the axial length of the cylindrical lens is finite, the total amount of light which is captured by the cylindrical lens decreases in the axially upper or lower area of the visual field. Also, the form of the intensity distribution is considerably distorted in the marginal areas of the visual field because of the optical characteristics of the lens. However, the difference between the address of the photocells which indicates the maximum intensity is not greater than two over the upper, middle, and lower areas of the visual field. This variation in detection of the address corresponds to the error of 2mm or less, in range, which will be allowable in measurement of human torso surface (Sheffer et al., 1986).

Figure 6 shows a example of the three dimensional shape of human back. These three-dimensional images are obtained by applying the stereometric system mentioned above. The shape data are linearly connected between sampling points before plotting in the scanning direction of the two scanners. Figure 7 shows an example of a wire frame model interpolated from the shape data shown in Fig. 6, by using B-splines of degree three. Such interpolation procedure will be needed so that the shape of back is well modeled.

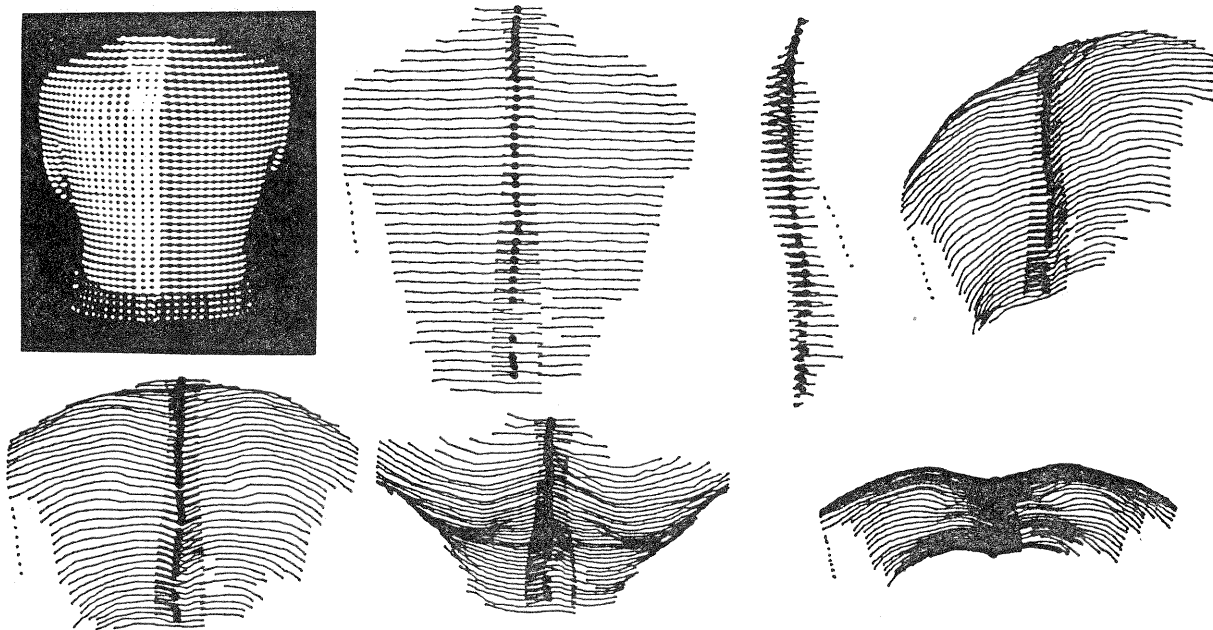


Fig. 6. An example of the locus of scanning under measurement (top left figure) and 3-D images of a human torso surface from different points of view.

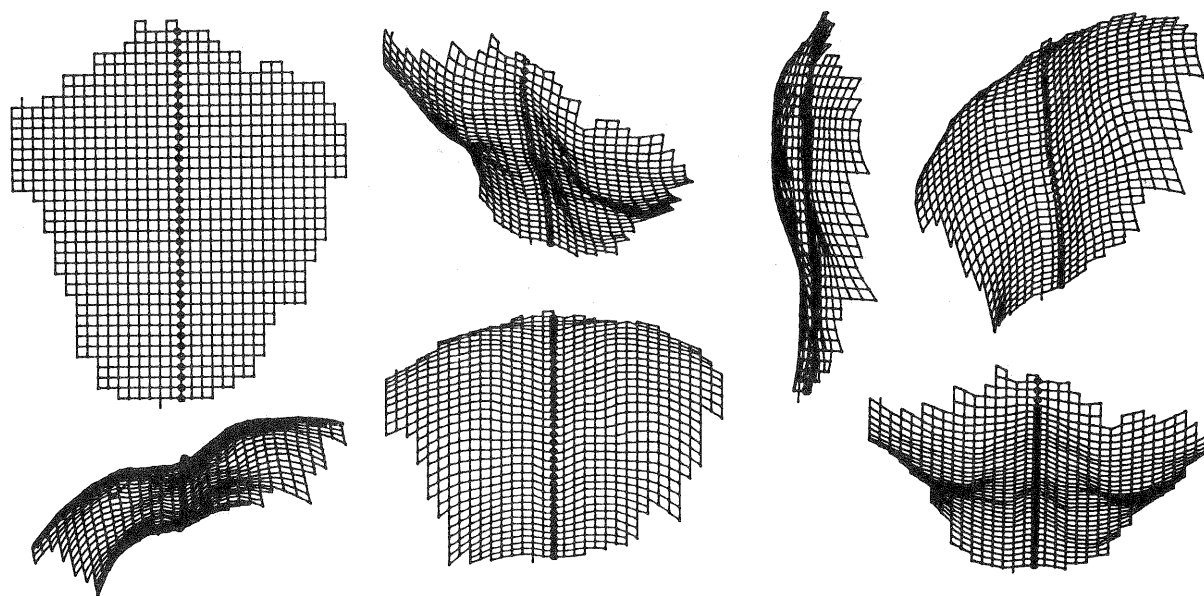


Fig. 7. A wire frame model interpolated from 3-D stereo data shown in Fig. 6 by using B-splines of degree three.

In this experiment, the time required for measurements was strongly affected by the reflection factor of the object surface because the signal-to-noise ratio in the intensity data from a photodiode depends linearly on the product of the intensity of illumination and the time interval of start pulses fed to the linear image sensor. It takes 60 to 80 seconds to measure 1,600 points on the torso surface.

CONCLUDING REMARKS

The stereometric measurement system described in this paper has several characteristics of importance to biostereometrics: arbitrary arrangement of multiple 1-D cameras, automated calibration of the camera parameter, automated stereometric data acquisition and automated reconstruction of 3-D shape with no image analysis. High-speed measurement of the shape of objects can be achieved by the combined use of cylindrical lenses and line sensors. The position of a light spot in $n*n*n$ pic-cells within a three-dimensional visual field can be reconstructed by detecting the output of only $n+n+n$ photodiodes.

Although at the present time the stereometric system is made on an experimental basis, the results in the preliminary experiments suggest a possibility of successful stereometrics and analytical representation of the 3-D shape of human torso and other objects.

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