BIOSTEREOMETRICS IN JAPAN

(Invited paper)

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ABSTRACT

Three-dimensionnal measurements of biological form and function have recently been attracting considerable attention in the life sciences. This survey includes a description of a variety of approaches to generalized three-dimensional measurements currently used in Japan. These include Moire photogrammetry, grating method, slit-lighting method, spot scanning method, coded-pattern projecting method, and stereometric reconstruction from binocular disparity. Special emphasis is placed on the microcomputer based stereometric measurement systems using solid-state sensors/cameras which enable us to make automated stereometric measurement at high speed. A perspective on their applicability and shortcomings in the context of biostereometrics is also discussed.

INTRODUCTION

Three-dimensional (3-D) measurement of biological forms and functions is a recurring problem in a variety of applications in the life sciences, including tomography, prosthesiology, cytology, biomechanics and ergonomics. While computer tomography and magnetic resonance imaging provide an excellent 3-D reconstruction of anatomical structures, several sophisticated methodologies have been developed for stereometric measurement of shapes, positions, spatial dimensions, movements, and their change over time. An important class of 3-D measuring methods deals directly with range information in order to determine the 3-D shape of objects. 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 elapsed time of pulsed-laser light (Tuchiya, 1984) or the phase shift in the reflected light of modulated-wave laser light. This method has the advantages that the "missing part," say, invisible region, is not included in the image. However, complex and expensive equipment including high-precision circuit devices will be required.

Triangulation can be subdivided into stereo disparity and contrived light methods. The stereo disparity method, referred to as passive, does not require any special devices, but has the drawback that for every point in one image one must find the corresponding point in the other image. To avoid this difficulty contrived illumination has been used. The active approach using contrived light sources includes spot and slit lighting, grid lighting, coded-pattern lighting and Moire fringe analysis. 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. These methods have different acquisition and processing time depending on their principles. As the required equipments and image processing are comparatively simple, the contrived light method is certainly acceptable in many situations.

Passive monocular image-based 3-D analysis includes texture gradient analysis, photometric methods (surface normals from reflectance), occlusion effects (relative depth), size perspective (diminuation of size with distance), distortion from known form (surface normals), and focusing methods. Under contrived lighting situations, an illumination of a diverging grid of lines provides the depth and orientation of local surfaces by "inverse" perspective.

The paper deals with several methodologies which are in current use or seems to be applicable in near future for biological and/or medical stereometrics in our country. First Moire fringe depth mapping is described. Then follow coverages of the contrived lighting stereometric methods. The passive binocular stereo disparity techniques are then addressed.

MOIRE FRINGE TOPOGRAPHY

A Moire fringe interference pattern formed by illuminating a measurement field with shadow patterns through an equispaced optical grating and viewing the field through an identical grating in a camera displaced laterally from the light projection system represents contours of equal range (Takasaki, 1970). The scanning Moire method (Idesawa et al., 1977) recovers the sign information indicating increasing or decreasing depth between adjacent contour lines and makes possible automatic measurement of the 3-D shape of an object. In this method, the second grating is replaced by a "virtual grating" formed by a set of equispaced scan lines of the video system. The virtual grating is equivalent to electrically sampling along these lines. Contour lines for different range levels can be produced simply by changing the phase or the pitch (spacing) of the sampling and contour change sign information is also recoverable from the order of emergence of contour lines for three or more different phases. The disadvantage of Moire method may be that, as the contour lines can be determined relatively over contiguous surfaces, the absolute range to a partially occluded surface cannot be recovered if there is no range contour continuum to that surface. Therefore Moire techniques may not be convenient for the purpose of analytically representing an entire surface.

The Moire topography has been widely utilized for mapping curved surfaces as well as for measuring small movements of a part of human body. 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. There are many

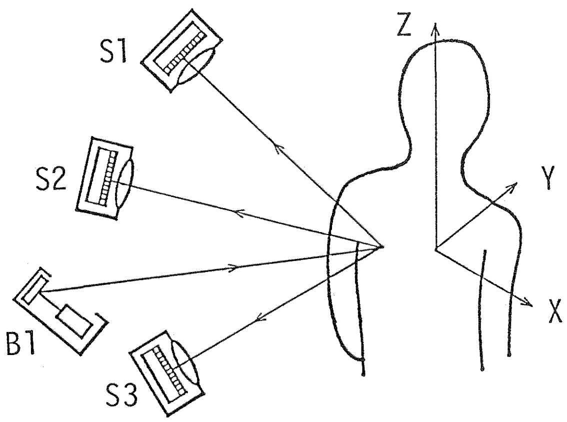


Fig. 1. A geometrical arrangement of multiple 1-D cameras (S1-S3) and a two-directional scanning beam (B1) for the spot scanning approach.

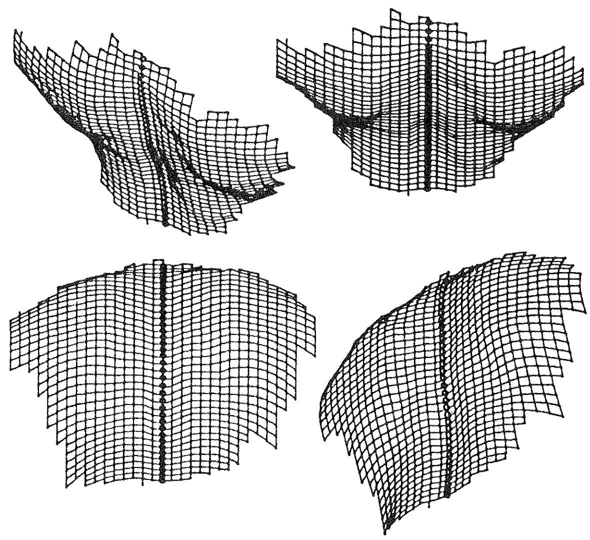


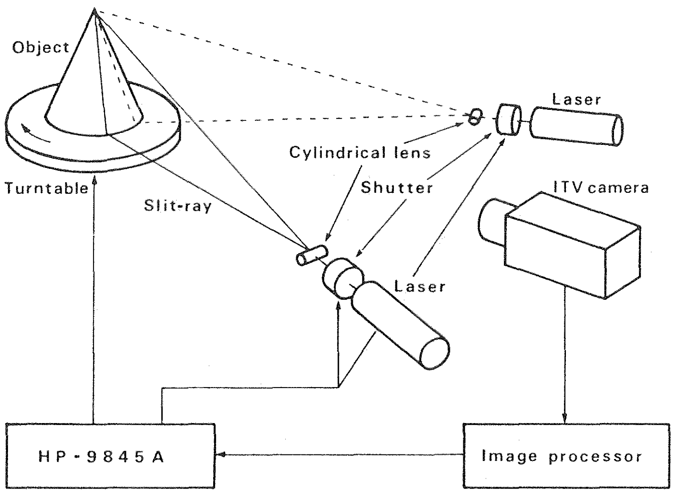
Fig. 2. An example of human back measured using the spot scanning method.

applications to medical use: measurement of shapes of standing posture (Suzuki et al., 1981), movement and volume change of rib cage on respiration, shape of face, arrangement of teeth, comparison of pre- and post-operative shapes of chest deformity, evaluation of scoliosis, and so on.

SPOT SCANNING METHOD

The most obvious method of absolute range finding is probably to use simply one spot at a time. A narrow beam of light from a source is scanned to form a light spot in the measurement field. The location of the light spot in object space can be computed by detecting the projected position in a detector, with known directions associated with source and detector orientation and the distance between them (Ishida et al., 1987; Harada et al., 1987; Nishikawa, 1981). Consecutive measurements of the light spot scanned over the surface of objects are sufficient to reconstruct 3-D shape of objects with no image analysis. The spot scanning stereometric systems proposed up to now employ TV cameras, solid-state imaging devices, or position sensing devices (PSD) as detectors and also, galvanometers, polygons, holographic grating, or acoustoptic deflectors for scanning the light beam.

In cases of the spot scanning approach, the accuracy of stereometric measurement is dependent on the resolution of scanning devices and/or detectors. Since a 1-D image sensor has, in general, higher resolution than 2-D image sensors, the 3-D measurement system using multiple 1-D detectors may be practical, expecting a greater working range as well as a reduction of uncertainty by redundancy (Yamashita et al., 1988). Due to its simple geometry and no image analysis, automated calibration of 1-D



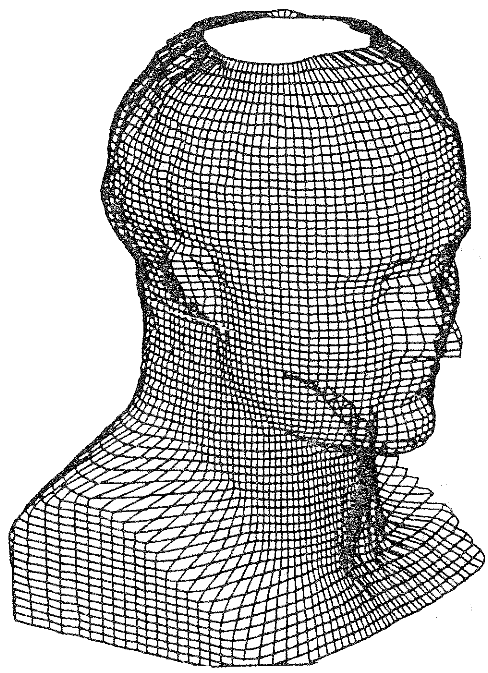


Fig. 3. Diagram of a measurement system using multiple slit-ray projections (left) and a measurement result of a plaster bust by projecting two slit-rays (right). (Sato et al., 1982)

camera parameters can be performed easily by measuring control points with known coordinates, which also makes possible automatic acquisition of 3-D data using three or more 1-D cameras. Figure 1 illustrates a geometrical arrangement of three 1-D cameras and one two-directional scanner for stereometric measurement of human torso surface. Figure 2 shows an example of 3-D images of real human back reconstructed using multiple 1-D cameras.

SLIT-RAY LIGHTING METHOD

A sheet of light is scanned across the measurement field and produces a single light stripe for each position. When a viewing TV camera is displaced from the slit-ray projector, the depth can be obtained by triangulation from displacements along a stripe. Since neither a complicated algorithm for finding correspondence between two images as in the stereo vision method, nor long time for the scanning as in the spot scanning approach would be required, this method has been widely used for nearly real time measurement of the range, shape, and position of a 3-D object, especially for the automatic assembling, sorting, and inspection of parts in an automated manufacturing (e.g. Ozeki et al., 1986), or for the eye of a robot. Under these circumstances, the object is observed from a single direction by a camera so as to obtain the shape information in real time, and accuracy is not considered to be so important.

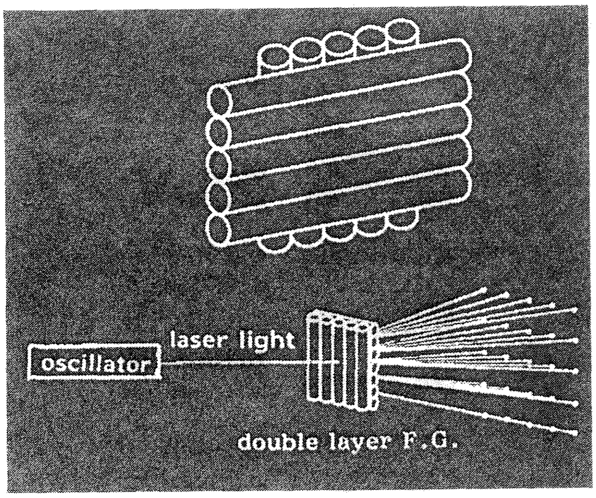


Fig. 4. A diverging diffraction of laser light by the double layer fiber grating. (Yamaguchi et al., 1983)

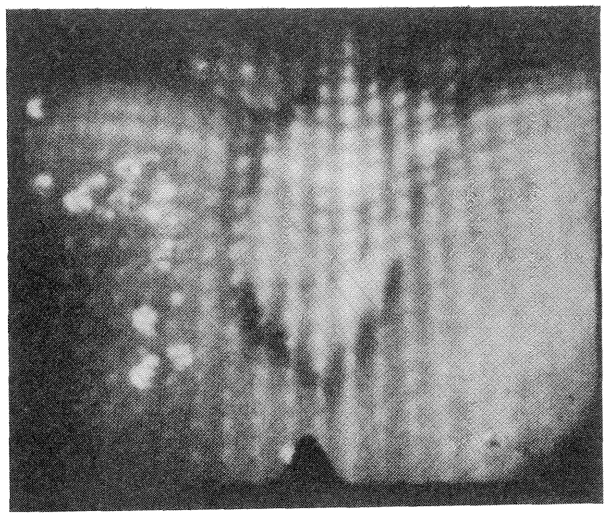


Fig. 5. Grid-illuminated gastric ulcer photographed by a laser endoscope. (Yamaguchi et al., 1983)

Multiple slit-ray projections may make possible more accurate measurement of 3-D shape, although identification of two or more stripes at a time in the measurement field becomes difficult. It was shown (Sato et al., 1982) that the exclusive problems, the accuracy and data deficiency of the measurement, can be solved by multiplication of the slit-rays and also that general objects in the real world, such as a human body, can be measured practically enough with only two directed projections. Figure 3 shows the measurement system using two slit-ray projections and a measurement result of a plaster bust, rotating the object on a computer-controlled turntable.

GRID CODING

The location and orientation of surface elements of an object can be extracted by illuminating a diverging rectangular grid of lines with high contrast. The distortion of an individual square from its original form in the projected grid provides the local surface orientations. The size perspective ("inverse" perspective which means enlargement of size with depth) of the diverging grid contains depth and area information of the local surface. This active monocular image-based stereometric method is applied for obtaining quantitative information about 3-D structure of tissue lesion on the internal wall through the endoscope (Yamaguchi et al., 1983). Figure 4 shows a double layer glass fiber grating which produces a diverging rectangular grid of spots by diffraction of laser light. This projector is mounted at the tip of the endoscope and the deformation of the rectangular array of the spots is measured at lens-object distance of 35mm to 90mm. Figure 5 shows an illuminated image of a gastric ulcer photographed by a laser endoscope.

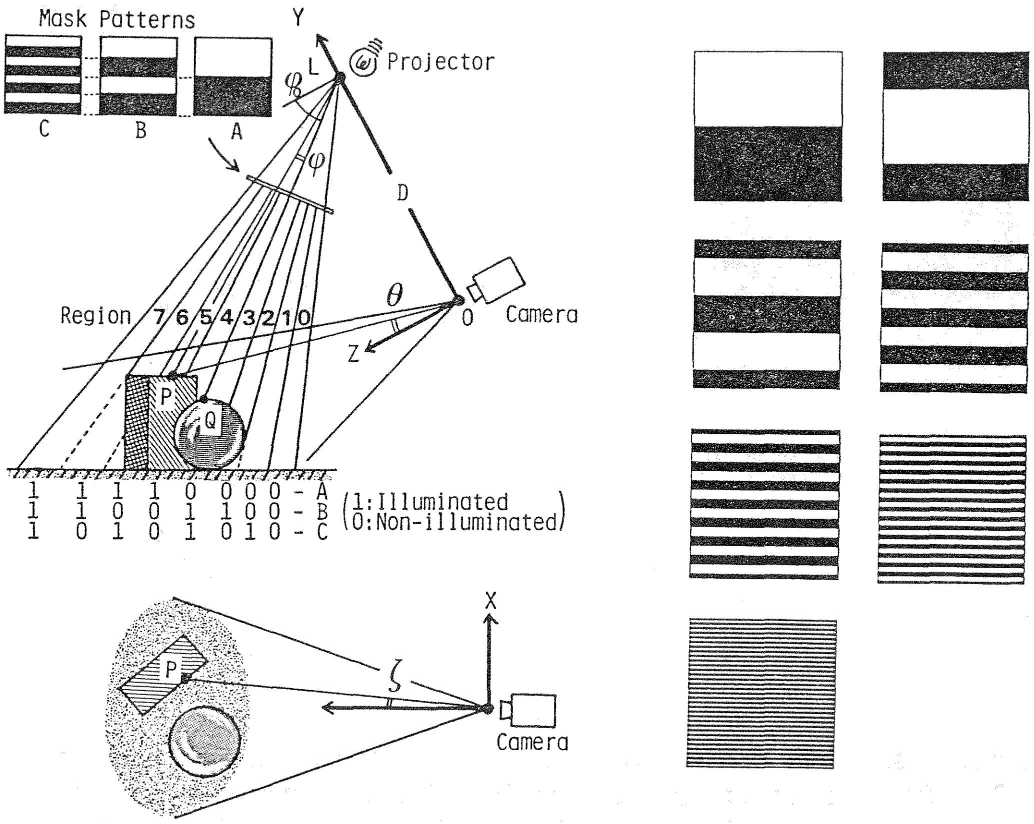


Fig. 6. Principle of stereometric method based on space encoding by projecting a set of binary coded patterns (left) and the Gray-coded projection patterns employed in the system. (Sato and Inokuchi, 1985)

CODED PATTERN LIGHTING

Space encoding by coded pattern lighting will make the correspondence problem resolved easily in stereo disparity analysis and also minimizes data acquisition time compared with spot- or slit-lighting approach. For instance, the projection of illuminated grids with an assigned address of 8 bit M series patterns can reject any error of stereo mismatching (Murai et al., 1986). Here, we describe a stereometric system using space encoding by Gray-coded binary patterns.

The stereometric system involves a Gray-coded binary pattern projector and a CCD video camera (Sato and Inokuchi, 1985). Figure 6 shows the principle of space encoding and position detection in case of vertical positioning, where the light source is placed above the camera. The object space is illuminated by a binary pattern projector and encoded into illuminated regions and nonilluminated regions. The point P on the object surface is encoded into illuminated region "1" by mask A. Similarly, it is encoded into "0" by mask B and into "1" (LSB in this case) by mask C. The wedge-shaped region including the point P is encoded into "101". (A set of pure-binary-coded patterns is used for the purpose of explanation, although the system employs the Gray-coded binary patterns as shown in Fig. 6.) Thus, a set of n Gray-coded patterns can encode the space 2^n wedge-shaped regions. Instead of scanning a slit light at 2^n positions in turn, only n patterns are required for space encoding. The use of the Gray code has the advantage that since the Hamming distance between the two adjacent numbers is always one, the ambiguity in space encoding on the boundary of the projection pattern can be limited within 1 LSB width of the pattern. An electro-optical device using a nematic liquid crystal can produce the 7-bit Gray-coded pattern with sufficient contrast and resolution (Inokuchi et al., 1972). Depth data of the point P is obtained from the projection orientation Ψ and the view-line orientation θ by using the triangulation principle. The depth recovery from the coded images can be performed well under a normal lighting by comparing two intensity images of the object: one without projection of coded pattern and the other with full illumination.

STEREO DISPARITY

It is well known that once stereo disparity between the left and right images is obtained, the depth information can be recovered from it on the basis of triangulation. The main problem of stereo analysis is in the correspondence of a pair of stereo images, assuming that each point in one image would have a corresponding point in the other image. In conventional stereo analysis, various hierarchical and global techniques have been used to establish correspondence or matching of points between the two images. For instance, in our country, there was proposed an adaptive threshold of the correlation coefficient on an adaptive window for match decisioning (Yasuye and Shirai, 1973), or a three-view stereo analysis method using three images taken from triangularly configured viewpoints so as to make the correspondence determination simple and reliable, from the consistency between them (Ito and Ishii, 1986). Although these approaches are useful in some cases, they often require a complicated and time-consuming algorithm to find correspondence. Nevertheless ambiguous matches cannot be avoided due to uniformity of intensity or occlusion effect.

BINOCULAR STEREO VISION

Human have two eyes for binocular stereo vision. The 3-D sensing capacity of humans depends not only on the eyes but also the neuron system. It is very interesting to develop stereometric methods based on knowledge about the structure and mechanism of the human visual system. A model of a binocular visual system has been made (Ohmori, 1986), which has the eyes and the neuron network controlling them. The neuron system consisting of many neuron-like operations also imitates visual information processes in the brain, extracting edge and depth information. However, such attempts are still under trial and the applicability to real situations is not good presently.

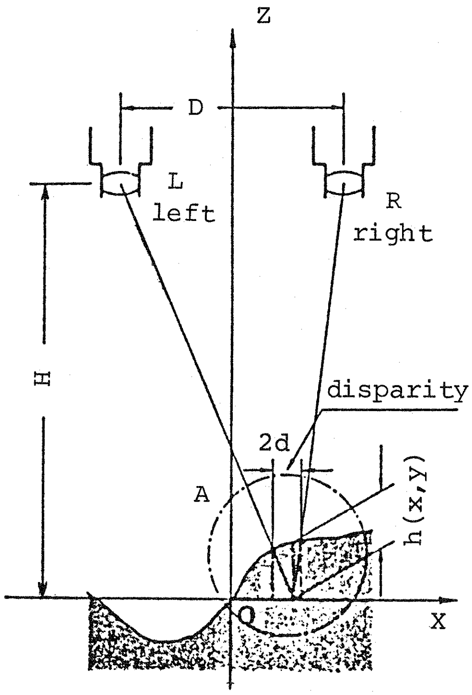


Fig. 7. Geometry of a binocular stereo vision system. (Ando, 1987)

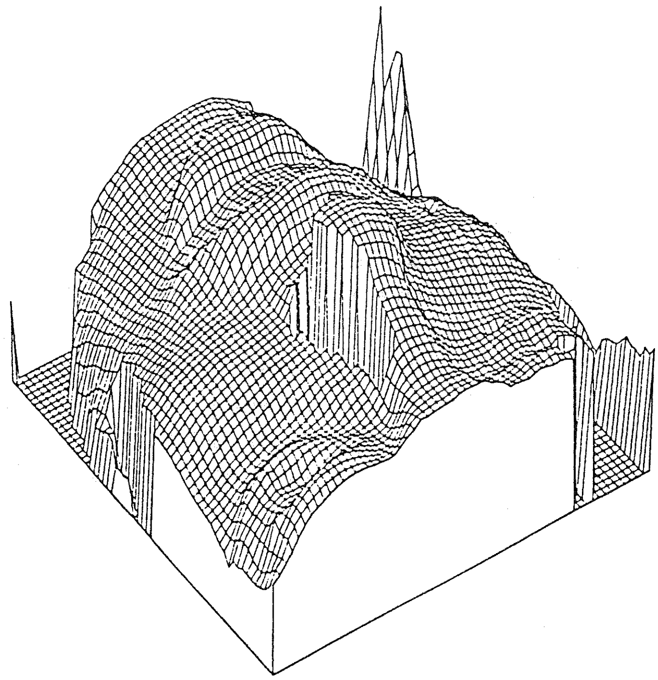


Fig. 8. An example of human face recovered by the binoculer visual system. (Ando, 1987)

From the standpoint of binocular stereo vision, a differential stereo vision algorithm should be reviewed (Ando, 1987). Figure 7 shows the geometry of a binocular stereo vision system. Two image sensors are assumed to be assembled so that their optical axes intercept the origin O of a common object plane (shown as z=0 in Fig. 8). The differential stereo vision method extracts a relative depth distribution with respect to this plane and then supplies us extensive information about the object shape near the plane. Let us assume that h(x, y) is the height distribution of the surface and f(x, y) represents the object intensity on the surface. In practice, the intensity distribution should be produced by illuminating a random pattern. The right and left images $f_R(x, y)$ and $f_L(x, y)$ can be given by the first order approximation of Taylor expansion:

$$f_R(x, y) = \bar{f}(x+d, y) \fallingdotseq \bar{f}(x, y)+\bar{f}_x(x, y)d, \tag{1}$$

$$f_L(x, y) = \bar{f}(x-d, y) \fallingdotseq \bar{f}(x, y)-\bar{f}_x(x, y)d. \tag{2}$$

Here $\bar{f}(x, y)$ implies the object intensity excluding magnification effect arising from a decrease of depth by h(x, y) and $\bar{f}_x(x, y)$ is its partial derivative with respect to x. Then the disparity d becomes

$$d = \frac{Dh(x, y)}{2(H-h(x, y))} = \frac{Dh(x, y)}{2H} \Big/ \frac{(H-h(x, y))}{H}. \tag{3}$$

By making the sum and difference of Eqs. (1) and (2), the local disparity d of a stereo pair must satisfy

$$\{\frac{\partial}{\partial x}(f_R(x, y)+f_L(x, y)\}d \doteqdot f_R(x, y)-f_L(x,y). \tag{4}$$

This differential identity with good symmetry has a meaning that a ratio of a difference image of left and right images against a derivative of a sum image is equal to the disparity. Applying local least squares estimation, one can obtain stabilized identity among statistical correlations between the sum and deference images. This gradient-based depth recovery for binocular vision systems has an excellent advantage of the parallel structure of algorithms so that it can be applicable to dynamical stereometrics in real time. Figure 8 shows an example of 3-D image of a plaster moulage of a human face reconstructed from the binocular vision system.

CONCLUSION

Several methodologies for stereometrics covered in this paper have been proposed with emphasis of applicability to biological and medical use. But they have advantages and disadvantages. What should be taken into considerations when applying these stereometric method to real biostereometrics is: size of equipment, easiness of assembly, automated calibration, accuracy and spatial resolution, measurement time, use under normal lighting, and requirement of in vivo measurement. Most methods presented are only applicable under specially controlled circumstances with high signal-to-noise ratio and few methods have been applied to real biological situations. We are expecting that new techniques could overcome the drawbacks and increase the feasibility status of various methods for particular applications.

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