Surgical Navigation System with Intuitive Three-Dimensional Display

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Abstract. This paper describes a newly developed surgical navigation system that superimposes the real, intuitive 3-D image of the patient's internal structure on the patient's body, and helps surgeons to perform surgery. The system consists of a personal computer, a lens array, a supporting stage, a liquid crystal display and a half-silvered mirror. The 3-D images are generated by real-time computer-generated integral photography, and superimposed on the patient's body via a half-silvered mirror, as if they could be seen through the body. The differences between the theoretical positions of the projected 3-D images and the recognized ones were found to be less than 3.8 mm, within an area of $100 \times 100 \times 40$ mm in the vicinity of the operation. The location of the point in the superimposed 3-D image could be recognized within an error of 3 to 4 mm. A 3-D bone image of a wrist joint superimposed on the corresponding part could be observed with correct motion parallax by more than one person and appeared to the observers as if it could be seen through the body. Because of the simplicity and the intuitiveness of the navigation image, this system will become applicable to clinical use in the near future.

1. Introduction

Surgical navigation systems have come to be widely used for many surgical fields. They usually show three-dimensional (3-D) information in pre-operation images to surgeons, as a set of two-dimensional (2-D) sectional images displayed away from the surgical area. Therefore, surgeons have to follow some extra procedures to perceive 3-D information of the patient during surgery. Firstly, they need to turn their gaze to the computer display showing the navigation images. Next, they must reconstruct the 3-D information in their minds, with the help of experience and anatomical knowledge. Lastly, they must turn their eyes back to the surgical area and register the 3-D information reconstructed in their minds with the actual patient's body. These procedures interrupt the flow of surgery and the reconstructed 3-D information sometimes differs between individual surgeons. To solve these problems, 3-D images

should be displayed three-dimensionally in the space that coincides with the patient's body.

The following requirements should be met for surgical navigation using 3-D displays:

1. Geometrical accuracy over the projected objects (especially depth perspective);
2. Visibility of motion parallax over a wide area;
3. Simplicity of application.
4. Avoidance of the need for extra devices, such as the wearing of special glasses;
5. Simultaneous observation by many people;
6. Absence of visual fatigue;

All of these requirements are important, especially 1, 2, and 3.

To meet all the requirements, we used the principle of integral photography (IP) proposed by Lippmann in 1908 [1]. Integral photography records and reproduces 3-D objects using a "fly's eye" lens array and photographic film (Fig. 1). Igarashi proposed a computer-generated IP method that constructs an image by transforming the 3-D information about the object into 2-D coordinates on the computer display, instead of taking a photograph [2]. However, the computing time for this method of creating IP was too costly and the system was not practical for rendering 3-D medical objects. To solve this problem, we have devised a new rendering algorithm for computer-generated IP and have developed a practical 3-D display system using it [3]. The 3-D location of the projected 3-D objects could be recognized within an error of 2.0 mm.

Fig. 1. How to record and reproduce a 3-D object by integral photography. Light rays reflected at a point on the 3-D object pass through the centers of all lenses on the array and are recorded on film. When the film is lit from behind, light rays intersect at the original point to become a new light point.

To superimpose the 3-D images on the patient, we used a half-silvered mirror that both reflects light rays and allows them to pass through it. The patient's body can be seen through the half-silvered mirror, and the projected 3-D image is reflected and can be seen at the corresponding position. This principle has been used for a similar purpose by Masutani et al. [4,5], who used stationary IP images of medical 3-D objects recorded on film and then superimposed them on the patient during surgery via a half-silvered mirror. Their method required several hours to record an IP image, and the image could not be altered, since conventional photographic film was used to record the images. Blackwell [6] used a binocular stereoscopic vision display system to show 3-D images. This display method reproduces the depth of projected objects by the fixed binocular disparity of the images. However, this does not always give the

observer a sense of depth, as this is created by the spacing of the observer's eyes, which is not always the same as that of the fixed lenses. Motion parallax cannot be reproduced without wearing a tracking device. As well as limiting the number of observers, this also causes visual fatigue, because although there are 2-D images on the displays, the observer has a remote 3-D sensation. Consequently, systems based on binocular stereoscopic vision are not suitable for surgical navigation display.

This paper presents a novel surgical navigation system with an intuitive 3-D display that can reduce the burden of procedures required to recognize 3-D information during surgery. The 3-D display designed for this purpose and the registration method for computer-generated IP are presented in Section 2. The accuracy of the recognized location of the projected 3-D image to the system and that of the registered image to the object are presented in Section 3. Associated problems and the feasibility of the system are discussed in Section 4.

2. Methods

2.1 System Configuration

The surgical navigation system developed in this study consists of a personal computer (Dual Pentium II 400 MHz), a hexagonal lens array (lens diameter: 2.32 mm), a supporting stage, a liquid crystal display (LCD; 6.0 inch, XGA, 213 ppi) and a half-silvered mirror (Fig. 2). The source image on the LCD is generated from the 3-D data by the algorithm described later in this paper. Any kind of 3-D data source, such as magnetic resonance (MRI) or computerized tomography (CT) images, can be processed.

Fig. 2. System configuration of the surgical navigation system with the 3-D display.

2.2 Three-Dimensional Display with Computer-Generated Integral Photography

In the proposed computer-generated IP, each point in a 3-D space is reconstructed by the convergence of rays from pixels on the computer display, through lenses in the

array. The observer can see any point in the display from various directions as if it were fixed in 3-D space. Each point appears as a new light source. A 3-D object can thus be constructed as an assembly of such reconstructed light sources.

Because the resolution of LCDs is much lower than that of photographic film, there is a decreased amount of information that can be displayed. Thus, not all points on a 3-D object can be displayed on the LCD, and only the 3-D information of the points most suitable to each pixel of the LCD can be processed. Coordinates of those points in the 3-D object that correspond to each pixel of the LCD must be computed for each pixel on a display. Fig. 3 shows the fast 3-D rendering algorithm for IP that computes coordinates of one point for each pixel of the computer display.

Fig. 3. Schema of a new, fast, 3-D rendering algorithm for IP. The line that occurs at the center of a pixel is extended through the center of the lens corresponding to the pixel. Then, the first point seen from the observer's side where the line intersects the 3-D object is displayed on the pixel.

Unlike natural objects, information about any point in the original object can be directly acquired in the case of medical 3-D images, making this method free from the pseudoscopic image problem that is peculiar to the original principle of IP.

The LCD is used to display the image without distortion. The plane that contains all the centers of the lenses on the lens array is used as the reference plane in the direction of depth. In the algorithm, D stands for the diameter of the lenses on the lens array; h the gap between the reference plane and the surface of the LCD; r the pixel pitch and H_i the distance between the reference plane and the i -th farthest point where two light rays radiated from two adjacent lenses intersect. H_i is calculated from the parallel relationship between the two triangles as shown in Fig.4, formulated as follows.

Fig. 4. Relation between H_i and other dimensions. P: pixels on LCD

H_i becomes the distance of the i -th farthest light point from the reference plane that is created by two adjacent lenses as an intersection of two rays, while i is a natural

number less than or equal to the number of pixels included in the radius of a lens, $D/2r$.

$$H_i = \frac{D \times h}{i \times r} = \frac{H_1}{i} \quad (1)$$

In the same way, given that $H_{i/j}$ is the distance of the i -th farthest light point created by two lenses, the distance between their centers is j -times the diameter of the lenses.

$$H_{i/j} = \frac{D \times j \times h}{i \times r} = H_1 \times \frac{j}{i} \quad (2)$$

Thus, the spatial resolution in depth is equal to H_{iMax} ($iMax$ is the largest number of i). As described above, the extent of the projection space can theoretically be much farther than H_1 , although the further the distance between a point and the reference plane becomes, the worse the quality of the point.

Fig. 5 shows a 3-D stationary image generated from a CT of the head. The image could be observed from various viewpoints with correct motion parallax.

Fig. 5. Photos of projected 3-D stationary skull images by IP taken from different directions. They demonstrate the ability of the system to display motion parallax. The letter denotes the position of the observer relative to the 3-D image: F: front, L: left, R: right.

2.3 Registration Method between the 3-D Image and the Patient's Body

Because the relationship between the location of the projected 3-D image and that of the navigation system can be found from calculation, registration between the 3-D image and the patient's body could be performed by registration between the navigation system and the patient's body. The registration was, therefore, performed as follows (Fig. 6).

(1) Coordinates of the point are measured by an optical tracking system (POLARIS, Northern Digital Inc., Ontario, Canada) and the measured value is directly used for calculation. Four points (P_{sys}) are pre-defined on the surface of the navigation system for calibration.

(2) MRI of the object is obtained, using four MRI markers attached to the surface of the object.

(3) The 3-D image of the object is rendered from the MRI by the above-mentioned method and projected by the navigation system.

(4) The position of the navigation system is adjusted manually so that the projected 3-D image roughly coincides with that of the object. Subsequently, the coordinates of P_{sys} are measured by the tracking device, and those of the images of the markers can be found by calculation.

(5) The coordinates of the markers on the object are measured by the tracking device. The position of the projected 3-D image is then transformed, as the four coordinates of the marker images coincide with the measured coordinates of the corresponding ones on the object. This procedure allows theoretical registration of the projected 3-D image with the object.

Fig. 6. Scheme of the registration method. The coordinates of the markers in the projected 3-D image can be found from the measured position of the navigation system by the optical tracking system. The position of the projected 3-D image can be adjusted roughly by manual movement of the system, and precisely by image transformation, so that the observer can see the 3-D image at the corresponding position.

3. Experiments

3.1. Accuracy of the Recognized Location of the Projected Point to the System

Because geometrical accuracy is the most important consideration for medical imaging, the accuracy of the recognized location of the projected point to the navigation system within the objective space was measured. A square with sides of 100 mm was displayed at a distance of 10 to 40 mm from the surface of the 3-D display and projected into the objective space away from the displayed location by the half-silvered mirror. The coordinates of the recognized location of the vertices and the

center of the square were measured by the optical tracking system. Five observers repeated the measurements three times for each vertex. The mean differences between the measured and the theoretical coordinates were less than 3.8 mm, within the space of $100 \times 100 \times 40$ mm (Table 1).

Table 1. Mean error of the measured coordinates.

Distance from display	Mean value (S.D.)
10.0	2.5 (1.4)
20.0	1.9 (0.6)
30.0	2.5 (1.3)
40.0	3.8 (2.5)

Unit:mm

3.2. Accuracy of the Recognized Location of the Registered Image to the Object

After registration, the position of the 3-D image theoretically coincides with that of the object. However, some errors in the recognized positions of the points in the image are inevitable. We therefore measured the accuracy of the recognized location of the registered image to the real object. A 50-mm cubic phantom object with four MRI markers (a vitamin E capsule filled with vegetable oil with a diameter of about 6 mm) on its surface and the same two markers inside the phantom was made of plate acrylic resin (Fig. 7). First, MRI of the phantom with six markers was taken and two inside markers were removed. Next, the 3-D image generated from the MRI was superimposed on the phantom with the above-mentioned registration method. Lastly,

Fig. 7. Scheme of the cubic phantom made of plate acrylic resin. The lower half was filled with agar. Mn (n=1~4) and Sn (n=1,2) denote the position of the marker attached to the surface and the inside, respectively.

the position corresponding to the two markers in the phantom were displayed in the 3-D image and their coordinates were measured three times by the optical tracking system. The mean differences between the measured and the true coordinates of the two markers are shown in Table 2. The errors were nearly equal to the radius of the marker.

Table 2. The mean differences between the measured and the true coordinates of the inside marker.

marker	mean error of the coordinates	mean error in length
S1	(1.58, 2.52, 2.83)	4.1
S2	(1.42, 2.34, 2.72)	3.2

Unit:mm

3.3. Trial of the Procedure from Data Acquisition to Superimposition of the 3-D Image

To examine the practicality of the system, we applied our procedure, from data acquisition to superimposition of a 3-D image, in a continuous manner. The wrist of a healthy volunteer was used as the object. An MRI image of the wrist was taken first. Images of the bones of the wrist and hand were segmented and superimposed on the corresponding part of the volunteer. It took about 2 h for the whole procedure, including data acquisition, segmentation, 3-D rendering and superimposition. The structures of the superimposed bone could be observed by many persons at the same time with correct motion parallax and appeared subjectively as if they could be seen through the body (Fig. 8).

Fig. 8. Position of the surgical navigation system and the subject (left) and the superimposed 3-D wrist joint on the real wrist (right). The internal structure of the wrist could be observed as if seen through the body.

4. Discussion

From the results of the accuracy test, it appears that observers can be guided by the navigation system within an error of 3 to 4 mm. This is insufficient, but allows for surgical navigation, because the surgeon can observe not only the navigation image, but also the real area during surgery. However, to minimize surgical invasion, navigation must be made more accurate. The spatial resolution of the 3-D image projected, using the principle of computer-generated IP, is proportional to the ratio of the lens diameter in the lens array to the pixel pitch of the computer display. Thus, both the lens diameter and, in particular, the pixel pitch need to be made much smaller. Judging from recent progress in the technology of manufacturing flat-panel LCD displays, this will soon be realized. Because the navigation system with this 3-D display is very simple and easy to use, we intend to apply this to such clinical uses as surgical planning and surgical navigation.

To conclude, we have developed a novel surgical navigation system with an intuitive 3-D display and have examined the errors in the recognized location of the projected object by using this system. The projected objects were geometrically accurate. Because of its simplicity and the accuracy of the image projections, this system will be able to be applied to clinical use.

Acknowledgments

We would like to thank Ryo Mochizuki (NHK Engineering Service) for lending us the super high-resolution LCD. This study was partly supported by the Research for the Future Program (JSPS-RFTF 96P00801).

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