I. INTRODUCTION

Anterior Cruciate Ligament (ACL) reconstruction is performed for ACL damage and knee instability, pain and recurrent swelling. In this surgery, surgeon makes tunnels on femur and tibia to fix the ACL graft. The positional precision of the graft insertion tunnel is important, since it directly contribute to the patient's rehabilitation after the surgery [1]. However, in minimally invasive surgery, most of operations are performed under endoscope, which requires expert skills for surgeons to grasp the internal structure of knee joint. Although X-ray fluoroscopy can be used to assist surgeons intraoperatively, limited number of images due to radiation exposure and restriction to two-dimensional (2-D) images are the problems. The objective of this study is to develop a navigation system which can display the real-time positions of femur, tibia and surgical tool in 3-D view.

Surgical navigation guides the surgeon by indicating the location of a tracking device through cross-sectional images, for example, X-ray computed tomography (CT), magnetic resonance (MR) images, or 3-D anatomical models reconstructed from such images. By localizing the targeted lesion and the critical lesion that should be avoided, the surgical navigation helps to achieve effective and safe surgery while minimizing the invasiveness of the surgery.

In previous study and clinical implementation, the display used for the surgical navigation system was often placed in a nonsterile field from surgeon. This forces the surgeon to take extra steps to match guidance information on the display with the actual anatomy of the patient [2]. This hand-eye coordination problem has been discussed in [3] as possible cause of the interruption of surgical flow. To overcome this problem, several groups have developed techniques that merge images into real-world views in a more natural and unconstrained manner. An example involves image overlay that visually merges a computer-generated anatomical model, reconstructed from medical images, with the patient's body [4]. Another example is the use of augmented reality visualization with microscopes or endoscopes in image-guided surgery [5].

We have developed an autostereoscopic image overlay technique that can be integrated into a surgical navigation system by superimposing an actual 3-D image onto the patient using a half-silvered mirror. This system can increase the surgical accuracy and reduce invasiveness. The autostereoscopic images are created by using integral videography (IV) [6], which is an animated extension of the integral photography (IP). IV record and reproduce 3-D images using a micro convex lens array and a flat display. The design presented in this paper is clinically unique as it is the first report of applying an autostereoscopic display in knee surgery with an image overlay system. Furthermore, we investigated a fast image rendering and displaying technique and patient-image registration method specific to IV-based navigation. We evaluated the accuracy of the navigation system by using a mock-up tibia phantom and a volunteer clinical trial.

II. SYSTEM AND METHODS

A. Application of IV image overlay to navigation

The computer-generated images of the anatomical object are rendered behind the lens array (Fig. 1a). The source image shown on the IV display is generated from the 3-D
data by IV rendering. Each point shown in a 3-D space is reconstructed at the same position as the actual object by the convergence of rays from the pixels of the element images on the computer display after they pass through the lenses in a micro convex lens array (Fig. 1b). The surgeon can see any point on the display from various directions, as though it were fixed in 3-D space. Each point appears as a different light source; a 3-D object can thus be constructed as an assembly of reconstructed light sources.

The coordinates of the points in the 3-D object that correspond to each pixel on the screen must be computed for each pixel on the display. The procedure is similar to the ray-tracing algorithm, although the tracings in this instance are directly opposite those observed on the screen. Our algorithm creates 3-D objects in the space between the screen and the observer, while the ray-tracing algorithm would place the object behind the screen. Unlike natural objects, information about any point in the original object can be directly acquired in the case of medical 3-D images, making our method free from the pseudoscopic image problems peculiar to IP.

We developed an IV rendering strategy that enables the surgical tools in an IV image scene. We first create IV images for the organs and the surgical tools and then combine them. The computing time required for both the anatomical object and the tracking device is approximately seven times that required for our proposed strategy.

Generally, the surgeon observed the operating field directly by eye during the operation. To ensure a smooth operation, the surgeon must indicate the target object, avoid critical areas, and respond to the intra-operative information when it is presented. The IV-based surgical navigation system developed consists of an IV display device, 3-D data source collection equipment, a position tracking system and a personal computer. The relationships between these elements are shown in the upper left part of Fig. 2.

B. Patient-image registration using optical markers and X-ray markers

Registration of patient-image can be based on a set of distinct features that can be accurately identified in both spaces. In this study, the fiducial markers used in image registration provide pairs of corresponding 3-D points in the spaces to be registered. A set of optical markers (POLARICS, NDI) are used to detect the position of femur, tibia and surgical tools. The same markers can be detected in X-ray and localized in the position sensor space by computing their 3-D coordinates. Once the coordinates of the markers in the image space and in the patient (knee) coordinate space have been determined, the geometric transformation that associates these two spaces can be derived. The registration process is as follows.
1) Calculate the projected matrix needed to transform from the coordinate system of the IV display to that of the projected 3-D IV image.

2) Calculate the rigid body motion of the IV display assembly relative to the optical tracking device.

3) Register the images to produce a patient preoperative representation with coordinate system. Mark the fiducial markers with a tracked pointer to indicate their position with respect to the physical space of patient.

4) Calculate the rigid body motion of the markers, therefore, of the patient and the intra-operative surgical tools relative to the optical tracking system.

Once all displayed objects have been transformed into the same coordinate space using these transformations, they will appear to the surgeon exactly as if they were in their virtual spatial locations (Fig. 2). This procedure enables theoretical registration of the projected 3-D image in conjunction with the target object.

C. High speed IV image rendering and displaying

Our approach in maximizing the rendering speed is to use Single Instruction Multiple Data Stream (SIMD) architecture computing along with volume rendering algorithm using potential field. SIMD computing in PC is further accelerated by Streaming SIMD extensions (SSE). Since the SSE support floating point arithmetic and operate on a register file, separated from the conventional floating point unit, we use inline assemble SSE code for the performance critical parts and compile the remains by using conventional floating point operations.

III. Experimental Evaluation

We conducted one set of experiments to assess the accuracy of registration by using markers in phantom; they were digitized in both a CT system and the optical tracking device. We conducted another set of experiments to assess the IV image rendering speed of bone model and surgical tools. For both two sets, we used a personal computer to render the IV images.

A. Materials

The IV display we developed consists of a high-resolution liquid crystal display with a micro convex lens array, a half-silvered mirror, and a supporting stage (Fig.3). The primary specifications of the IV display are listed in Table I.

A phantom of tibia bone is used to evaluate the registration accuracy of image-to-patient. The phantom is fixed by an optical tracking tool, which embedded a set of optical markers and CT markers. They were used to register the IV image within the physical space of the phantom. The CT image data for the phantom consisted of one set of coronal images with 0.24×0.24-mm in-plane resolution and 0.6-mm slice thickness.

B. Registration accuracy experiment

The purpose of the first set of experiments was to assess the accuracy of the registration process. The IV image generated from the CT was superimposed on the phantom.
using the registration method described above. The physical coordinates and displayed position of the markers in the IV image were both measured with the optical tracking system.

The accuracy of the measurement was determined by comparing the position measured manually through the IV display with actual physical position. Four different operators used the optical tracking device to measure the position of markers in the three IV image overlay experiments, and compared the results with the physical position of the measured point. They repeated the measurement ten times for each distance. The statistical distributions of registration error for markers are shown in Table II. The mean value of the difference between the measured and physical coordinates of the markers was 1.16 mm and the standard deviation was 0.60 mm.

<table>
<thead>
<tr>
<th>TABLE II. REGISTRATION ERROR OF PHANTOM EXPERIMENT</th>
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<tr>
<td>IV image 1</td>
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<td>A</td>
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A: axial; S: sagittal; R: right.

C. Evaluation of rendering time

The rendering time depended highly on the complexity of the rendered object. Despite of the complexity of the data, the original algorithm also depended on the size of the volume data. With our optimized algorithm, the rendering time was shortened. The benchmark test showed maximum 399 percent performance gain with clinical data achieving 11.3 frame per second (Intel Pentium 4, 3.2 GHz CPU).

D. Clinical trial of IV image overlay

A volunteer clinical trial was implemented to evaluate the feasibility of the developed navigation system. We performed CT scanning to take photo of in-vivo knee. The volumetric CT images of knee (512×512pixels×347 slices, thickness of 0.5mm) were segmented and the results were rendered and transmitted to IV display. We integrated IV segmentation image in knee surgery and superimposed IV image into the patient in surgical implementation (Fig.5). These combinations enabled safe, easy, and accurate navigation.

Fig. 5. Clinical trial of knee joint surgery by use of IV image overlay.

IV. DISCUSSIONS AND CONCLUSION

We have demonstrated a unique autostereoscopic image overlay technique for surgical navigation. An actual 3-D image is superimposed onto the patient using a semi-transparent display based on an adaptation of integral videography to image overlay. Two major experimental findings demonstrated feasibility of the proposed technique. The registration accuracy was 1.16 mm on average, which is almost satisfactory for image-guided knee joint surgery. The error between the lens pitch and the width of the element may have also caused the deformation, thus affecting the depth perception significantly on deep locations.

Although updating the IV image of an anatomical object remains computationally costly, advances in computer hardware technology should soon obviate this problem. It will then be possible to register an anatomical object’s intra-operative configuration with the surgical instrument in real time, based on real-time data gathered using a real-time image scanner or from deformation calculations.

Experiments have shown that our real-time 3-D surgical navigation system can superimpose a real and intuitive 3-D image onto a patient’s body for accurate and less-invasive surgery. The real-time IV algorithm we developed for calculating the 3-D image of surgical instruments was effective in representing the real-time location of both surgical tools and knee during an operation. The experimental results show that the errors were in the range of about 1 mm. Due to the simplicity and accuracy of real-time projected point location by the introduction a display device with higher pixel density, this system should be of practical use in the ACL reconstruction surgery and other medical field.

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