Performing virtual surgery with a force feedback system

Naoki SUZUKI1, Asaki HATTORI1, Shigeyuki SUZUKI2, Takahiro KUMANO3,
Akio IKEMOTO3, Yoshitaka ADACHI3, Akihiro TAKATSU1

1 Institute for High Dimensional Medical Imaging, Jikei University School of Medicine
4-11-1, Izumihoncho, Komae-shi, Tokyo 201-8601, Japan
e-mail: nsuzuki@jikei.ac.jp
2 School of Science and Engineering, Waseda University
3-4-1, Okubo, Shinjuku-ku, Tokyo 169-8050, Japan
3 Suzuki Motor Corporation R & D Center
2-1, Sakuranamiki, Tuduki-ku, Yokohama 224-0046, Japan

Abstract

We are developing a surgery simulator which would enable surgeons to perform various kinds of surgical maneuvers in virtual space using VR techniques. Furthermore this system would be able to manipulate patient oriented 3D structures of the body as elastic objects in real time. The system employs a force feedback device that supplies the user with a sense of touch. As the device is attached to right and left hands, both of the user's thumbs, forefingers and middle fingers can feel the force and elasticity of skin and organs when pinched or compressed. The deformation of which is observed simultaneously on a real time 3D image.

1. Preface

Numerous studies show that surgery simulation is one of the largest applications of medical virtual reality [(1)~(6)]. In 1998 we presented our virtual surgery system equipped with force feedback functions in the ICAT97 [(7)]. In the former paper, we presented our trial to obtain a sense of touch with the patients' organs in a virtual space. In this paper, we would like to present the results of the extended project. This system permitted physical manipulation of elastic organs utilizing force feedback device attached to each users hand.

2. Elastic organ models for the system

In order to reproduce an elastic organ appropriate for our system, we developed a sphere filled model method instead of applying the finite element method. The sphere filled method reconstructs a patient's organs as a surface model filled with small elements. The radius of each sphere is identical and they are filled up at a face-centered lattice in the organ model. The external forces generated by the users' fingers or tools displace the contacted element spheres. Those displaced element spheres in turn displace the surrounding spheres until the shape of every sphere in the organ ultimately changes. The new location of the element sphere determines the new altered surface of the organ models. The sum total of the magnitude and direction of the displaced element spheres can be used as a parameter of force to drive the force feedback system in order to create a sense of touch. If the external force exerting pressure on the organ ceases, the element spheres realign in their original position and the organ shape recovers its original shape much like an actual elastic organ.

We have improved this system primarily in two areas; final processing speed and system responsiveness. At first, we enhanced the efficiency of element sphere displacement calculation. Second, we enhanced the efficiency to calculate any interference from neighboring organs. We also attempted to correspond the performance in order to grasp the organ surface at a pinpoint. With the former system, precision was limited to an area equivalent to the mass held between 2 or 3 fingers. In other word we couldn't grasp precise points such as those located at the middle part of a polygon of the organ model's surface. To overcome this limitation we subdivided the polygon at the location of the pinch point and then accurately generated an identical point located at the work position. We used a high-speed graphic workstation Onyx Reality Engine[2] and infinity reality (Silicon Graphics Inc.) for this system. The communication and data transportation networks between the graphic workstation and force feed back devices are constructed by the Internet.

3. Force feedback device for both hands

When considering the virtual surgery system with sense of touch for practical use, it is important to realize that the system possesses a facility to generate a physical sense of touch unlike those imitated by sound or a mechanical vibration. The user, in particular, requires a perception of the organ surface's elasticity or the weight of the organ tissue's mass. In order to provide these facilities in our force feedback device, we needed to create the following two mechanisms. First, we had to erect a system able to continuously and accurately measure the users' hand movements and that worked in conjunction with the control manipulator system. Second, we had to build a force control manipulator for each finger. Especially in the case of surgical works, we need accuracy in each finger's force control manipulators. However, if we had built a long manipulator sufficient to cover the surgical work area, its sensitivity would have decreased due to its own weight. Furthermore, complicated finger action may have interfered with an adjacent manipulator. If we had shortened and consequently reduced the weight of the force feedback manipulators, the user's work area would have become smaller than the work area for surgical manipulation. In light of these problems we designed a structure that fixed the short and light force feed back manipulators to the top (distal part) of the motion control manipulator which covers a larger work area. Fig.1 shows the basic composition of the force

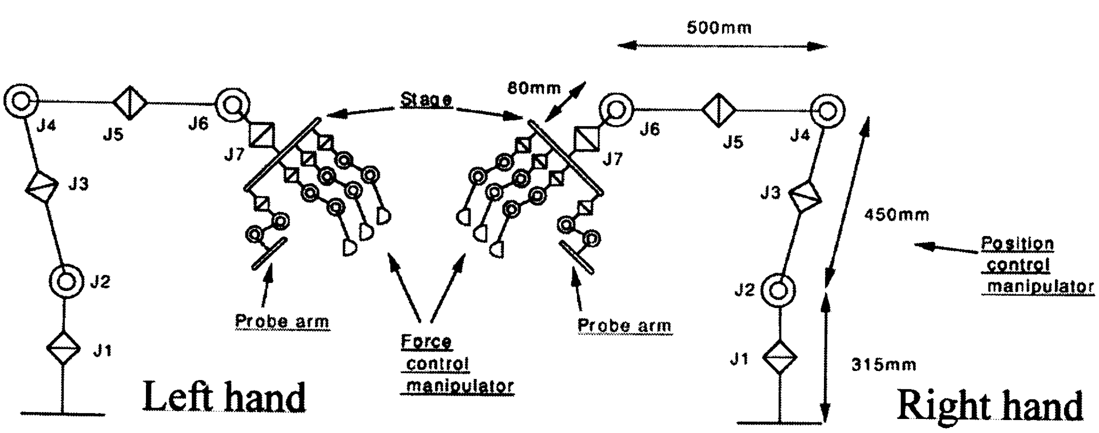

Fig.1 Block diagram of the force feedback device

feedback device. Both right and left force feedback devices have the same internal structure. The force feedback manipulator for the left hand is a mirror image of that of the right hand. On both hands, the force control manipulator producing the sense of touch is attached to the thumbs, forefingers and middle fingers of the right and left hands respectively.

4. Results

4-1 The elastic organ model

Fig.2a,b shows the reconstructed model of the abdominal region consisting of the skin, liver and stomach. An original 3D dataset for these models were obtained from a patient in 2mm pitch with 2mm slices using MRI. From the 3D dataset, the skin surface, the liver and the stomach contours were determined and made into sphere filled models. The number of sphere elements of each organ was determined by fixing the radius of each sphere element adequately. Fixing the radius is important because the system's response speed is influenced by each sphere's radius.

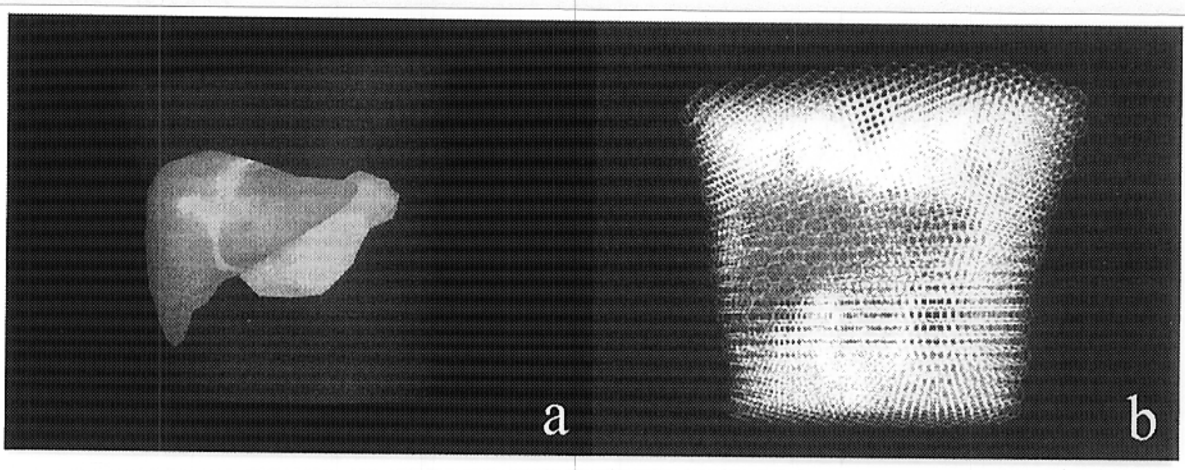

Fig.2 Reconstructed model of abdominal region including liver and stomach

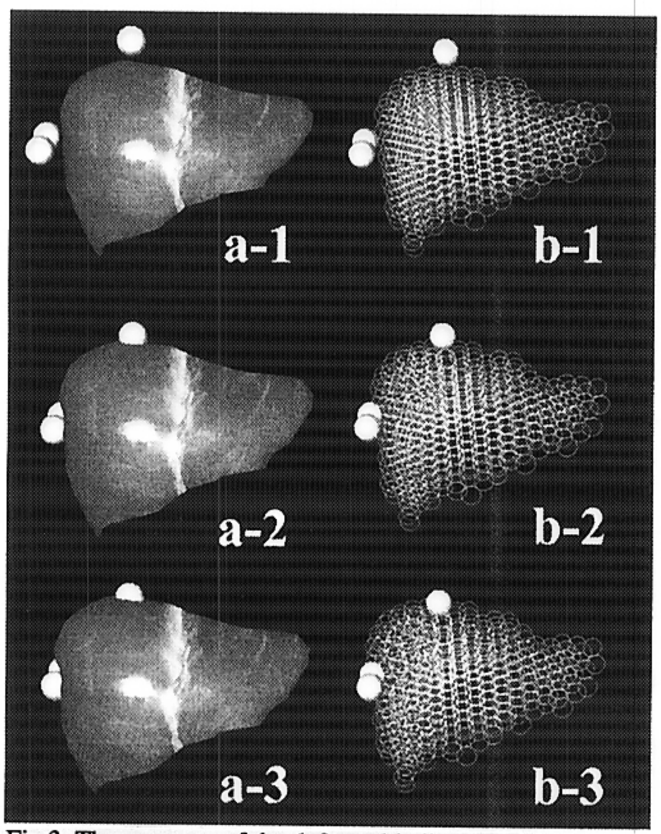

Fig.3 The response of the deformable liver model with 3 fingers

The liver model was constructed with 1880 sphere elements. Fig2.a shows the organ's outer surface and the body surface while Fig.2b shows the sphere-elements' condition filled in the forementioned surface models. In Fig.2a, the liver surfaces and that of the stomach is wrapped within a texture image of the organ. This texture information is not related to the patient and was stored texture obtained from an extracted organ specimen. There are dual reasons for using this texture information for the simulation. First, the movement of a partial organ surface due to deformations is very easily recognizable when it is textured. In contrast, it is rather difficult to see color painted organ models. Secondly, the authentic appearance of the texture mapped organ would assist students requiring clinical experience in medical education. The user could personally select the process between texture mapping and color painting. Fig. 3 shows the liver model response when three external forces simultaneously pressure its surface. In this figure, three liver models on the left side are texture mapped while those on the right side illustrate the condition of the sphere elements within the surface model. Three white spheres indicate the position of the user's fingertips. Beginning from the upper image, a series of progressive sequences illustrate how three fingers grasp the liver's upper right lobe. The change on the liver model surface caused by three external forces could be seen on the left side while its inner structures are seen in the right images. The average response speed rate was from 9 to 20 frames / sec. in all cases. However, it was revealed that response speeds were largely affected largely according to changes of the depth limit of the element spheres' movements.

4-2 Link with force feedback devices

Fig.4 shows the force feedback devices attached to the user's hands. Fig.5 shows the linkage between the device and the real time image. The user's hand is perceived as a 3D image in order to identify its location as it comes in contact with the liver surface. When the liver surface was compressed on the image the user's finger detected touch. In the 3D image experiment, the response speed was from 7 to 14 frames /sec. Fig. 6 illustrates the time sequential change of the force supplyed to a forefinger when derected by the force feedback model. The chart shows a linear progression as the user's finger twice contacted the liver surface. When the user attempted to reduce the contact pressure while in mid-movement the sphere filled model responded and measured the magnitude in time sequenced forces.

Fig.4 An demonstration of force feedback devices for right and left hands

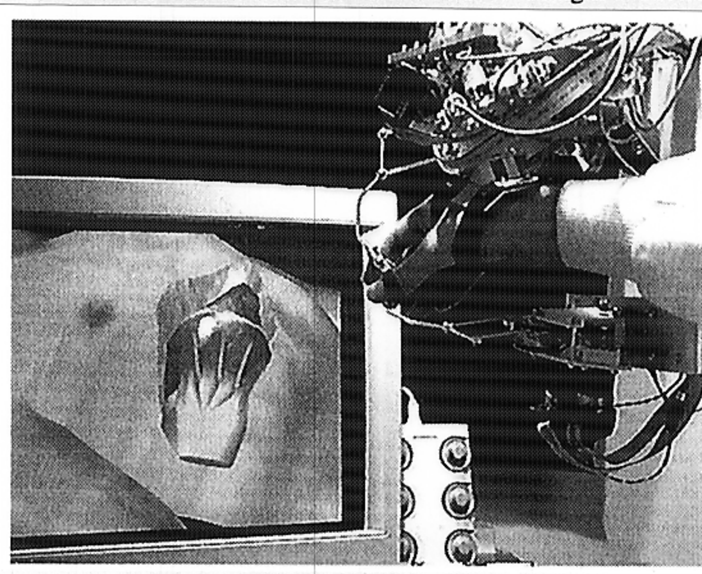

Fig.5 An experiment to push a liver surface with the manipulator of 3D image

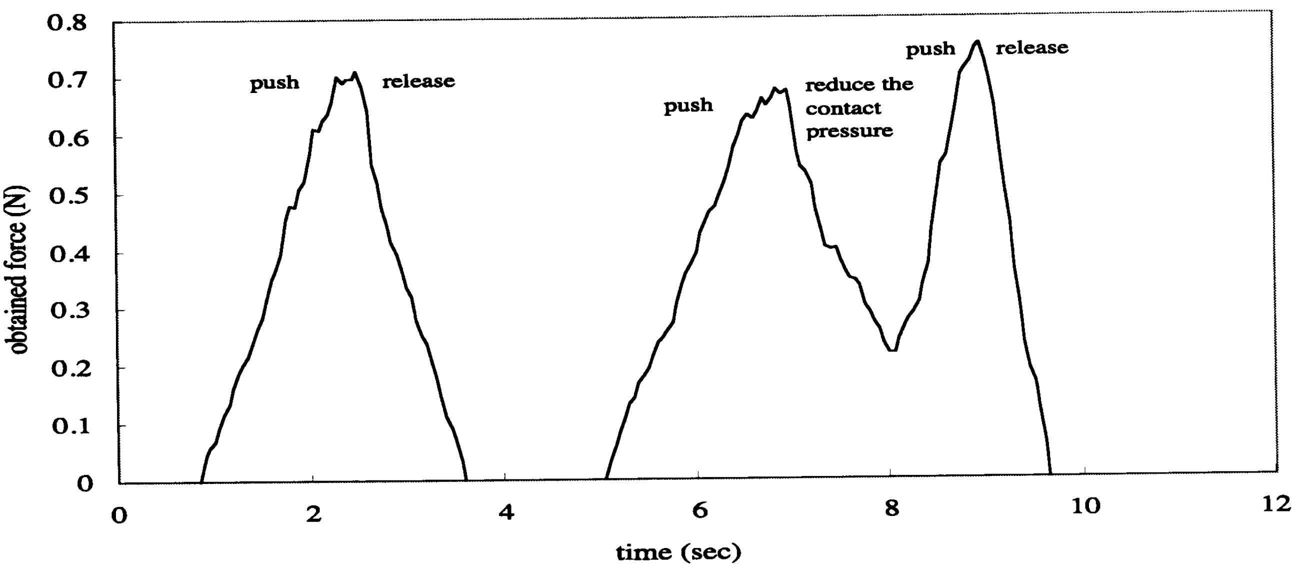

Fig.6 Time sequential change of the obtained force to a forefinger by the force controlled manipulator

5 Discussion

5-1 Elastic organ model

Although we made limitations on the diameter of the element spheres and the depth to which the spheres are movable (limit layer of spheres), we did make it possible to handle elastic organ models which possess 3D anatomical structures of the patient in real time. Thus, we would like to emphasize our method's merits as compared to those of spring models [8][9] or finite elements [10][11] . At first, (1) It is possible to construct an organ model semi-automatically unlike the considerable manual and pre-process work required with spring or finite elements. However, in our case, the model construction process can be completed by determining the organ contours and filling them with element spheres. (2) These procedures could be applied to neighboring organs and soft tissues (see Fig.2a,b). Thus, contact with neighboring organs is possible without specially calculating the interference with neighboring soft tissues. (3) As deformation is determined by the repetition of a simple calculation of element sphere movement, it is possible to obtain high speed performance. (4) Because the number of displaced element spheres is stable, it is possible to keep the organ's definite volume without any special calculations. (5) The direction and magnitude of the sense of touch is easily obtained by the integration of displaced element spheres. Therefore, it is possible to generate the sense of touch in real time because response speed is not effected by the number of fingers touching the organs.

5-2 Force feedback system when equipped to each hand

We would like to point out the following merits of our force feedback devices. (1) We obtained good mobility and low inertia from the finger manipulators fingers by shortening the length of the force feedback manipulators. (2) Complicated finger actions do not interfere with each other due to the base positioning of the force feedback manipulators on the opisthenar. (3)It was possible to obtain sufficient work space by changing the length of the motion control manipulator. Though the length of the force feedback manipulators was short, it was possible to obtain a large work space with good mobility. This was accomplished by tracking the hand movement rapidly with a motion control manipulator that loaded the force feedback manipulators at its distal part. Finally we obtained a 400mm square work space which in our opinion is adequate to perform various surgical maneuvers.

5-3 Assessment of the total system

Using our system, we were able to physically manipulate an object that included skin surfaces and a liver model at a speed of 7 to 14 frames /sec. Also the user's three fingers on both the right and left hand were able to perceive a sense of touch through interactive actions. We are going to develop this system in order to perform complicated surgical maneuvers in various parts of the body. We believe that these kinds of VR simulators will be helpful for clinical surgery planning and for educational medical training.

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