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A Haptic Navigation System for Supporting Master-Slave Robotic Surgery

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Abstract

Conventional display in robotic surgery such as flat displays or stereoscopic displays decreases obtainable information around target tissue. For supporting manipulation and performing safe surgery, this paper proposes a haptic navigation method, which enables surgeons to avoid collision with untouchable regions around target tissue by producing force feedback through a master manipulator. This paper also developed an input interface for assignment of 3D untouchable regions through 2D device. Simulator based experiment clears effectiveness of the proposed haptic navigation for improving safety of robotic surgery.

Key words: Haptic Augmented Reality, 3D Input, Intraoperative Support

1. Introduction

Conventional master-slave type robots were mainly developed for supporting limited works in dangerous place like atomic power plants. In recent days, master-slave type robots have been introduced as a powerful tool for minimizing invasiveness of surgery. Several surgical robots like ZEUS® and da Vinci ™ [1] are introduced in a variety of surgery. The advance of robotic surgery is a hot topic for improving patient's quality of life.

In current master-slave type robotic surgery, surgeons operate manipulators with visual feedback through monitors. However, such feedback has several problems due to the limitation of input/output hardware such as cameras and displays. A foregoing study [2] reports lack of depth information interferes recognition of 3D positional relationship between robot manipulators and target tissue. Because accurate and careful operation is required to perform safe surgery, lack of 3D information is a serious problem for surgeons. In order to enhance recognition of 3D relationship between manipulators and target tissue in the surgical field, development of information support is essential.

This study proposes practical haptic navigation to support manipulation in master-slave type robot surgery. This concept aims not only to assist surgeons for grasping 3D positional relationship between robot arms and target tissue but also to prevent the manipulator from collision with untouchable tissue like nerves or other delicate tissue. To present a specific solution to the concept, this paper firstly proposes a 2D clickable interface for setting 3D untouchable region quickly on measured 3D MRI volumes. Secondly, this paper presents satellite point based haptic augmentation techniques which perform stable and consistent force feedback.

The practical use of this approach gives advanced application of haptic augmented reality (AR) in the field of surgery. A robotic microsurgery simulator with haptic navigation is preliminary developed for evaluation. Effectiveness of the proposed methods is examined through some trial of functions and user study.

2. Significance of Haptic Navigation

As described in chapter 1, current robotic surgery forces surgeons to acquire surgical view via 2D flat display. In case of 2D images acquired from a single camera, surgeons have to estimate 3D relationship between a manipulator and tissue from limited information. Although stereoscopic display is implemented into da Vinci surgical robot system [1] for example, the stereoscopic image does not present complete depth or distance from a target object. Other vision-based or auditory-based methods [3, 4] are also proposed. However, they cannot directly produce enough information like 3D direction and distance from untouchable tissue, which are necessary for safe operation.

Master-slave type robotic systems not only display visual information through monitors but also present force feedback by controlling a master manipulator. Compared to other information support technologies, haptic navigation has the following advantages.

- A force vector can represent 3D relationship (direction and distance) between manipulators and target tissue
- Force feedback is directly conveyed to user's hands, and notify him of the approaching state quickly and intuitively
- Small data size of a force vector is suitable for network communication and tele-robotic surgery

Also, in conventional surgery, haptic feedback has been playing important roles in both recognition and manipulation of surgeons, which reveals haptics is an important sense similar to vision for careful operation. Thus, haptic navigation has possibility of improving safety in master-slave type robotic surgery.

3. Haptic Navigation System and Methods

3-1. Design of Haptic Navigation System

This chapter explains the concept and total design of haptic navigation. Careful analysis of master-slave type robotic surgery reveals some requirements or current goals for performing practical haptic navigation listed as follows:

(a) A simple input interface enabling interactive setting of 3D untouchable/touchable region on target tissue:

In order to establish haptic navigation, definition of 3D dangerous region, which is untouchable for surgeons, is needed. Because the region is dynamically updated depending on the situation of the surgery, a simple input interface is required to set or to release untouchable region interactively.

(b) Stable force generation reflecting position of robot hands and target tissue while handling 3D shape of the manipulator:

An effective force feedback scheme is essential to avoid collision between the manipulator and dangerous tissue like nerves. A force vector should be calculated based on 3D position of the slave manipulator and target tissue. Stable force generation is obviously a key for safe navigation. Handling 3D shape of the slave manipulator is also important for practical use. Actually, movable area of the robot hand is restricted, and insufficient recognition of its shape and size may cause unexpected contact on delicate tissue.

This study focuses on these requirements and defines a haptic navigation system based on the proposed input interface and haptic augmentation methods of which details are described later. The total design of the system is illustrated in Figure 1.

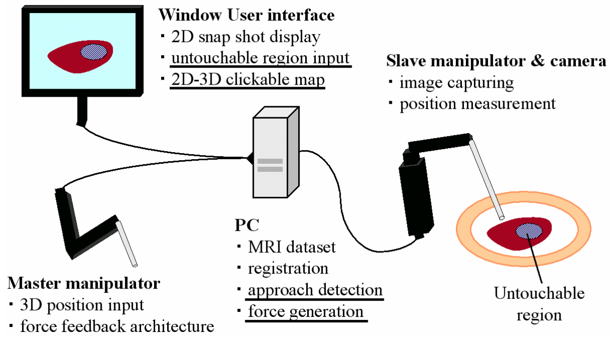

Fig. 1: Total design of haptic navigation system. This paper focuses on setting of untouchable region and stable haptic augmentation.

This system is specifically designed for master-slave type robotic surgery using OpenMRI. The haptic augmented surgery is started after setting untouchable region on a 3D voxel object, which is reconstructed from measured 2D MRI images. The system obtains positional relationship between the slave manipulator and untouchable region in real time, and presents repulsion through the master manipulator based on the proposed force feedback scheme. If the untouchable region is moved or changed together with process of surgery, the surgery is interrupted while the surgeons re-define untouchable region on the next virtual organ reconstructed from newly measured MRI images.

3-2. Clickable Input interface of 3D Untouchable Region

Requirements for 3D input interface

The input interface of the proposed haptic navigation system needs to fulfill the following requirements.

- Fast setting (or release) of untouchable region
- Intuitive input via a 2D screen
- Designation of 3D region on a 3D voxel object

These functions efficiently enable surgeons to change the definition of untouchable region during surgery. However, inputting 3D region on 3D models is generally a difficult task. So far, some techniques [5] have been proposed to support designation of polygons via 2D devices. However, because surgeons do not have enough time to designate all polygons of widespread untouchable region during surgery, it is essential to establish a sophisticated input interface to let user to define 3D region immediately.

3D Region Input via 2D manipulation

This study utilizes captured snap shots of surgical fields and provides an efficient clickable interface to set untouchable region on 3D shapes via a mouse. Figure 2 illustrates outline of the fast 3D region input method.

Firstly, the proposed system extracts regions from the 2D snap shot of the surgical field using color and depth information of target tissue, and provides a 2D map (2D–3D voxel map) which has some labeled regions.

Secondly, registration between the snap shot, the 2D map and 3D MRI volumes is completed on the screen. This registration enables to make specific links between all labeled 2D regions (e.g. region A and B) and 3D surface regions (e.g. object A and B) on MRI volumes. When the user clicks a point of a labeled 2D region on the 2D snap shot, the system defines the related 3D voxels as untouchable region. Thus, the proposed interface enables the user to set the untouchable region by one click.

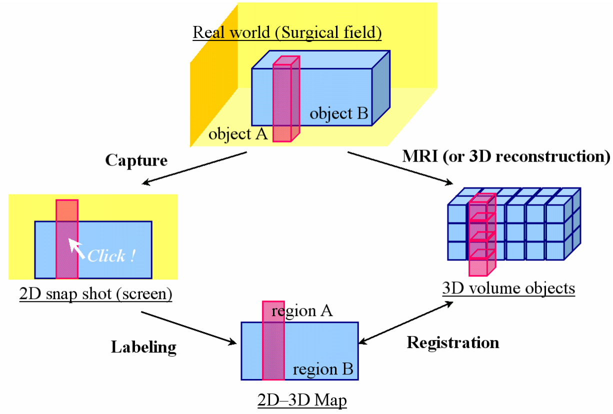

Fig. 2: Fast 3D region input via 2D device. Clicking a point on the 2D snap shot, related 3D voxels are selected.

The 2D-3D voxel map used in selecting untouchable regions requires some color-labeled regions on the snap shot. Fast Labeling Algorithm [6] is applied to create the label using the pixel value clicked by the user. Because the surgery is interrupted during this labeling step, calculation time for creating new 2D map should be kept as short as possible. Since the calculation cost of Fast Labeling Algorithm is O(n) (n: total number of pixels), it is effective for generating 2D map in real time.

3-2. Clickable Input interface of 3D Untouchable Region

Mapping Function

The proposed haptic navigation method defines a force field using the relative position of the slave manipulator and target tissue. Next, force feedback is displayed to the surgeon via the master manipulator and prevents from misleading the robot hand to untouchable region. The force field is defined based on a mapping function that aims to generate stable repulsion suitable for safe manipulation.

This study tested some mapping function through some experiments for improving safety of surgical manipulation, and selects a mapping function for collision avoidance which generates repulsion proportional to distance between the manipulator and the untouchable region. Figure 3 (a) shows an example of the applied mapping function. Figure 3 (b) illustrates a sectional image of an example of the force field that is defined by the mapping function.

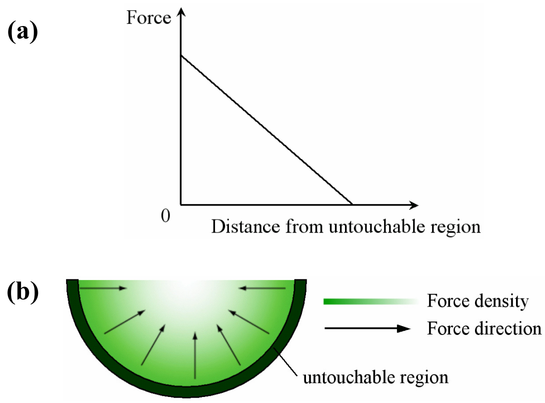

Fig. 3: (a) Applied mapping function to draw the manipulator back from untouchable region and (b) Sectional image of the force field defined by the mapping function given in (a).

Satellite Point Based Approach Detection and Stable Force Feedback

In order to generate force before colliding with the untouchable region, this approach detects approaching state by improving haptic rendering techniques [7]. Several haptic rendering algorithms are currently proposed especially in the field of virtual reality. Although single point-based collision detection algorithm [8] enables fast computation, it cannot represent 3D shape of the slave manipulator. On the other hand, multi-point model efficiently simulates 3D shape of the manipulator and achieves valid computational cost [7, 9]. The multi-point model handles 3D shape using several sample points on the surface of the manipulator.

This study applies the advantage of the multi-point model to haptic augmentation. The image of the proposed approach is illustrated in Figure 4 (a). In the proposed model, sample points (called satellite points) are not located on the surface of the manipulator but cover the whole body of the manipulator like aura. This extension of the covering area is useful to acquire approaching state before contacting the target object.

Although the multi-point based model gives a valid solution for real-time computation, the force feedback scheme has a possibility of generating unstable force in some cases. Especially, if the number of sample points is not adequate, the calculated force vector sometimes changes drastically. Such unstable force feedback clearly has a bad influence on safe manipulation. Inconsistent force generation is another problem of the multi-point model.

In order to solve these problems, this model employs the max size of normal vectors on sample points for magnitude of total force vector (Figure 4 (b)). This modification of the model gives stable force which is not related to the number of sample points. Also, the generated force is independent from 3D shape of untouchable region.

4. Evaluation and Results

Based on the proposed methods, a microsurgery simulator with haptic navigation in neurosurgery was preliminary developed. As a master manipulator, PHANToM (SensAble Technologies Inc.) haptic device was implemented. 3D anatomical virtual object of brain stem, nerves and target tumor was constructed and voxelized. (Figure 5(a)).

0.03 sec is required to carry out region labeling using depth and color value of the virtual object. Figure 5 (b) shows the generated 2D map that includes some labeled regions. Using the map, nerves are set as untouchable region. 2D-3D voxel mapping technique enables to set 3D untouchable region by one mouse click through labeled 2D snap shots of the surgical field.

In order to evaluate the haptic augmentation technique, the authors compared the force generation with conventional methods [7, 9]. 26 satellite points are located around a cylinder type manipulator. Satellite force is defined using the mapping function: $y = 0.35 \times x$. Where y is satellite force of a satellite point and x is distance between the current satellite point and its contact point with untouchable region. Calculated force vector was measured while moving the manipulator to the given untouchable region. As shown in Figure 6, the proposed model stably detects approaching state around untouchable tissue.

This study prepares one simple task for the experiment in order to verify efficiency of haptic navigation. The examinees try to move a manipulator from an initial point to an assigned goal while avoiding the untouchable region. Errors and elapsed time are counted under the condition with/without haptic support. 16 medical students who have no experience of operating master-slave robots joined to the experiment. In order to reduce bias of procedural order, the examinees are divided into two groups of which condition is listed in Table 1.

Table 1. Condition of the experiment procedure

	Group 1	Group 2
N	8	8
Proc. 1	Practice with no support	Practice with haptic support
Proc. 2	Practice with haptic support	Practice with no support
Proc. 3	Task with no support	Task with haptic support
Proc. 4	Task with haptic support	Task with no support

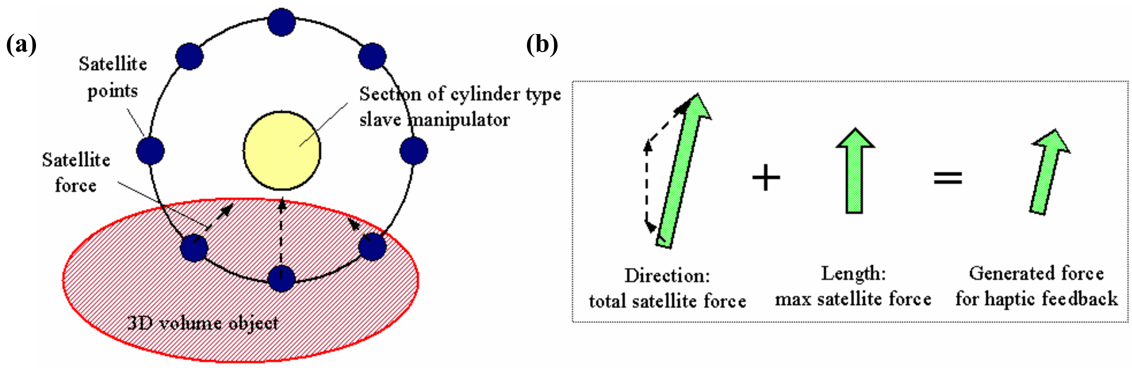

Fig. 4: (a) Satellite point model for haptic augmentation: satellite points detect approaching state of slave manipulator and (b) Stable and consistent force generation for haptic feedback

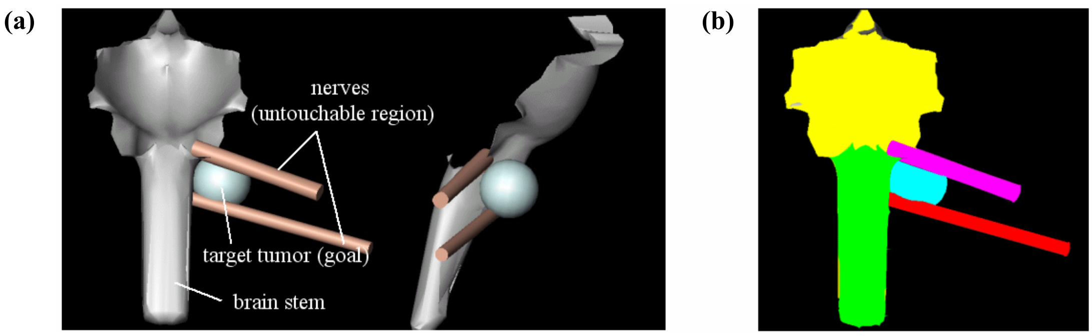

Fig. 5: (a) 3D anatomical objects used in microsurgery simulator. The examinees try to move a manipulator to several points on the target tumor while avoiding nerves. (b) 2D clickable map to assign 3D untouchable region. Each region is connected to related voxels.

Figure 7 shows average and variance of both error number and elapsed time. Also, significance probability between two groups is given in Table 2. The figures demonstrate haptic navigation is significant for decreasing total number of errors. On the other hand, no difference is revealed on the elapsed time. These results confirm that the proposed haptic navigation efficiently supports surgical manipulation by avoiding collision with the untouchable tissue. Moreover, the manipulation is not prevented from haptic augmentation.

Table 2. Average and significance probability

	no support	haptic support	cut off (p)
Elapsed time (sec)	62.8	69.6	0.348
Number of errors	3.15	1.15	0.007*

5. Conclusions

This study proposes practical haptic navigation methods for supporting master-slave type robotic surgery. Compared to forgoing approaches, the authors (1) developed 2D clickable interface using the 2D-3D voxel map which enables quick setting of 3D untouchable region on measured 3D volumes, and (2) solved unstable and inconsistent problems in force generation by extending the haptic rendering methods to haptic augmentation. Note that the algorithm considers 3D shape of the manipulator.

In order to evaluate overall methods, the authors developed a neurosurgery simulator with haptic navigation. The experiments confirmed the methods efficiently support surgical manipulation by avoiding collision with the untouchable tissue. Reducing total error with haptic navigation contributes to perform safe manipulation in robotic surgery.

Acknowledgements

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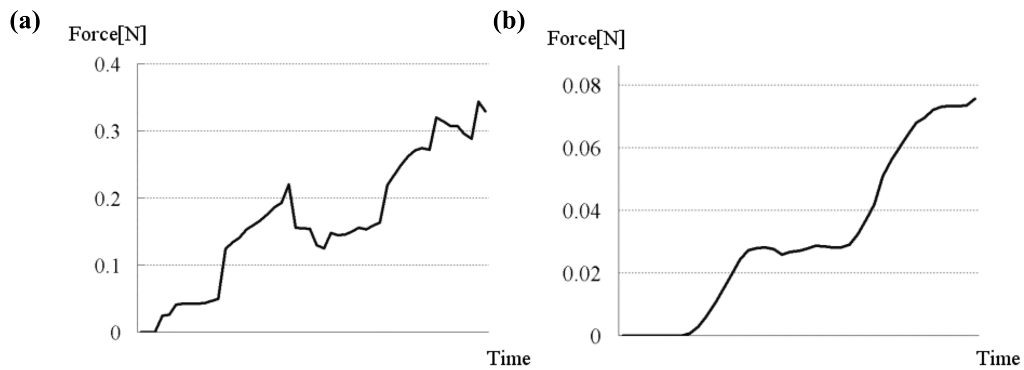

Fig. 6: Evaluation of force feedback, (a) related haptic rendering model [7], (b) proposed haptic augmentation model.

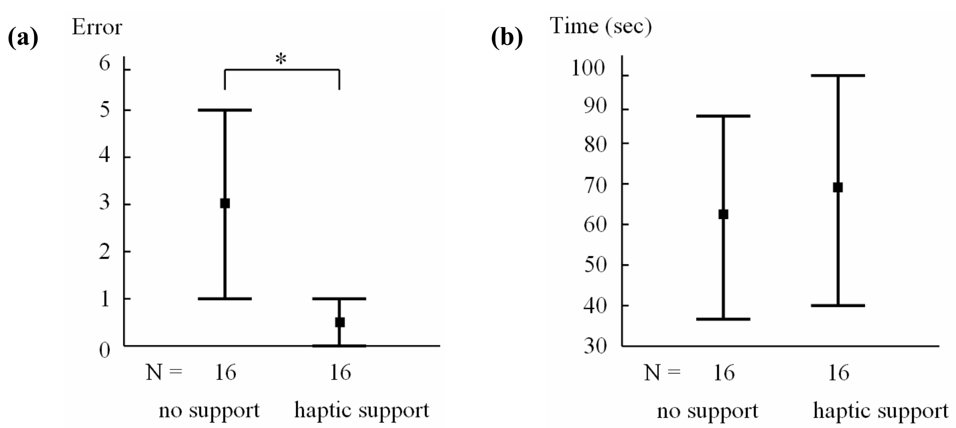

Fig. 7: Results of preliminary user study: (a) errors and (b) elapsed time. The proposed methods reduce total errors without disturbing surgical manipulation.

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