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A Laser-Pointing Endoscope System Providing the Operational Support of Surgical Robot

Mitsuhiro Hayashibe Yoshihiko Nakamura
Hiroyuki Shimizu Masafumi Okada
(E-mail: [hayasibe,nakamura,hshimizu,okada]@ynl.t.u-tokyo.ac.jp)
Department of Mechano-Informatics
University of Tokyo
7-3-1, Hongo, Bunkyoku, Tokyo 113-8656 Japan

Abstract

Precise measurements of geometry should accompany robotic equipments in operating rooms if their advantages are further pursued. For deforming organs including a liver, intraoperative geometric measurements play an essential role in computer surgery in addition to pre-operative geometric information from CT, MRI and so on. We developed a laser-pointing endoscope using an optical galvano scanner and a 955fps high-speed camera. The laser-pointing endoscope system acquires and visualizes the shape of the area of interest in a flash of time. Applications of the system also include the touch screen interface for non-master-slave operation of surgical robots, where the 3D coordinates of the touched point on screen are measured by the system and guide a robot. Results of in-vivo experiments on a liver of pig verify the effectiveness of the proposed system. The intraoperative 3D model of liver could be useful to avoid the collision with forceps of surgical robot by 3D geometric calculation in the abdominal space.

Key Words: *medical robotics, minimally invasive surgery, endoscope, laser scanner, 3D geometry*

1 Introduction

Endoscopic surgery forces surgeons to operate with mental tension under the mechanical and visual constraints. The visual difficulties are due to narrow sight of endoscopes and the lack of depth perception. Minimally invasive surgery would be technologically improved if surgeons are provided with the 3D shape of internal geometry and the 3D coordinates of the point of interest in an intuitive manner. The related and significant as well would be the issue of human interface. As minimally invasive surgery allows more and more technology involvement[1], tighter but more natural relationship between machines and surgeons are required. The *Zeus* of Computer Motion Inc.[2,7,8] and the *da Vinci* of Intuitive Surgical Inc.[3], for instance, choose the master-slave configuration, where the human interface is still limited to direct manipulation.

Fig. 1: Laser Pointing Endoscope

In this paper, we develop the laser-pointing endoscope system and realize safety management by intraoperative geometry. We fabricate a prototype using a galvano laser scanner and a 955fps high-speed camera. This device allows to acquire the intraoperative 3D geometric information in a flash of time. We also propose a touch screen interface so that surgeons can intuitively indicate 3D points of interest on the 2D screen. As an application of the interface, we develope a non-master-slave manipulation system for the surgical robot. Results of in-vivo experiments for a liver of pig verify the effectiveness of the proposed. We propose and realize the safety management using intraoperative geometric information.

The prototype was developed as shown in Fig.1 employing a laser light source, a 2D galvano scanner, two endoscopic optics, two cameras of different standards and a LCD monitor with touch screen interface[4]. Being controlled by the mirrors of galvano scanner, a laser spot is projected inside the patient's body through an endoscopic optics. The laser spot is captured by a 955fps high-speed camera (DALSA Inc.; 256×256 pixels, 256 gray scale) and an image capture/processing board (Viper-Digital; CORECO Inc.). The image of high speed camera is not suitable for the surgeon's monitoring. Information from high speed camera is used only for 3D geometric information of organs. Using a beam-splitting prism, color images of the same scope are captured by an NTSC CCD camera and presented to the surgeon.

The laser and camera coordinate systems are identified by OPTOTRAK (Northern Digital Inc.) attached to the devices. The 3D coordinates of reference points are reconstructed based on the triangulation[5] between the high-speed camera image and the mirror angles of galvano scanner. Although the image captured through the endoscope is distorted by the relayed lens inside[9], it is corrected and used to calculate the 3D position. Fig.2 shows the scanned surface of 50yen coin by laser-pointing endoscope. The hole on 50yen coin could be measured and the error is within 1%.

The scanned 3D data is automatically redescribed in Virtual Reality Modeling Language 2.0 by the our developed program. The shape of liver is easily percieved by www browser with VRML plug-in software. The surface is composed from numerous triangle patches as shown in Fig.3. These combination of points which form the triangles are used for geometric computation to check the collision between objective models.

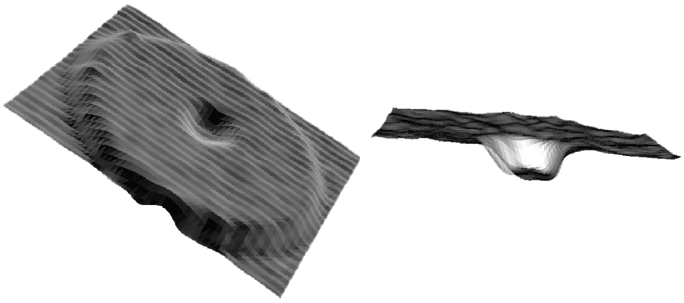

Fig. 2: Scanned surface of 50yen coin

2 Intraoperative Geometric Information and Surgical Robot

Using intraoperative geometric information obtained by the laser-pointing endoscope, we developed the geometry-assisted surgical robot system as shown in Fig.4. This system is composed of the laser-pointing endoscope and a surgical robot with its controller and the device coordinator. Every device is connected to a PC, which is linked with others by a shared memory board to facilitate real-time data transmission. The shared memory board (Memolink) enables the data transmition at the rate of 2M Byte/sec.

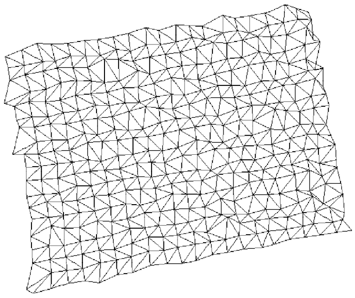

Fig. 3: Wire frame model of the reconstructed VRML

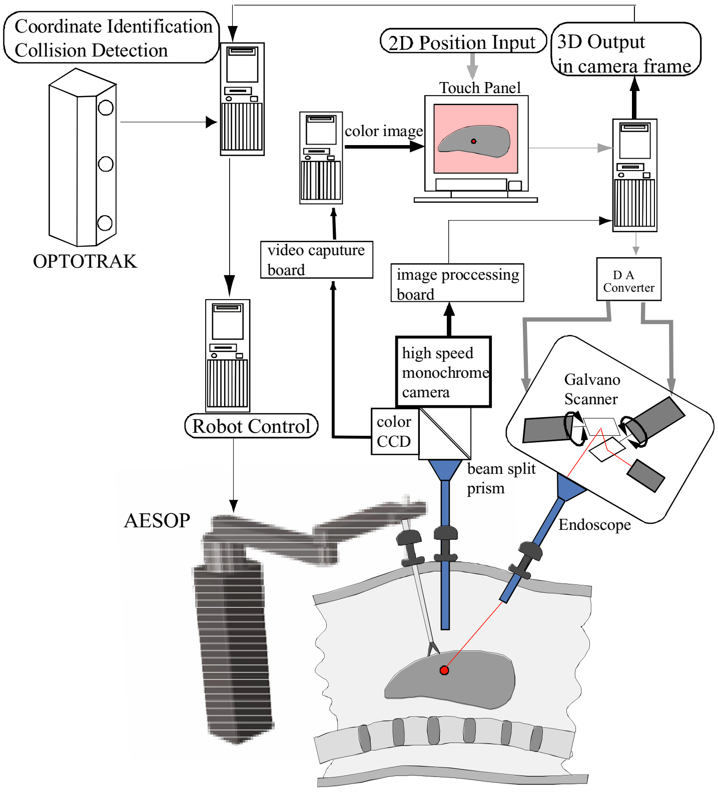

Fig. 4: System configuration

The laser-pointing endoscope obtains the intraoperative geometry of the objective organs in high-speed. The obtained geometric information is registered into the virtual space. The coordinates of device are measured by OPTOTRAK and the optical markers. The motion of surgical robot is monitored in the virtual space. The geometric model of surgical robot and the scanned organ model are combined and integrated in the virtual space. The models are used for intraoperative monitoring and collision detection between organs and surgical equipments. The surgeons are able to see as a virtual view the wider scope inside the body even though it is out of the real view from the endoscope. The geometric interference computation can inform surgeons of unexpectable collision in advance even in the case of teleoperative robotic surgery.

3 Intraoperative Monitoring of surgical robot motion

3.1 Geometric Modeling

In this research, AESOP (Computer Motion Inc.) is adopted as the surgical robot to have forceps. AESOP is originally designed for laparoscope positioning. AESOP have 6 joints including 2 passive joints. The link parameters of these 2 joints are passively decided by constraint of the hole on the abdominal wall. To guide the forceps, we redeveloped the robot controller to control the 3D tip position of forceps attached to AESOP.

The modeling of AESOP is done based on the shape of link and link parameters as shown in Tab.1. The geometric link shape is described in local link coordinates in VRML2.0. Fig.5 shows the wire frame model of AESOP.

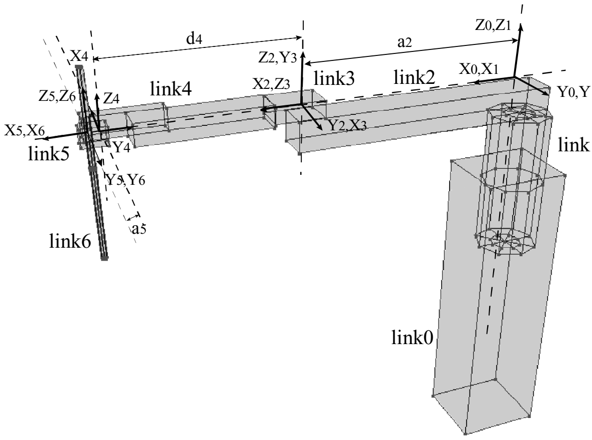

Fig. 5: Wire frame model of AESOP and local frames

Table 1: Link Parameters of AESOP

• • • •	• • • •	α	a	d	$\cos\alpha$	$\sin\alpha$
1	d_1	0	0	d_1	1	0
2	θ_2	0	a_2	0	1	0
3	$\theta_3+\frac{\pi}{2}$	$\frac{\pi}{2}$	0	0	0	1
4	$\theta_4+\frac{\pi}{2}$	$-\frac{\pi}{2}$	0	d_4	0	-1
5	$\theta_5-\frac{\pi}{2}$	$-\frac{\pi}{2}$	a_5	0	0	-1
6	θ_6	0	0	0	1	0

3.2 Motion data transmission to model

As a command to AESOP, absolute 3D position extracted by Laser-Pointing Endoscope is used to guide the tip of forceps to the destination on the organ. The controller generates the linearly interpolated objective position from initial position and destination in every sampling time. Fig.6 shows the flow chart of AESOP control. Using synchronous flag, joint angles are transmitted into that of the virtual model in every 10ms. The controller always observe the emergency stop flag, which is put if the interference between the robot and the organ is detected. Fig.7 shows the activated virtual model by the motion data of surgical robot.

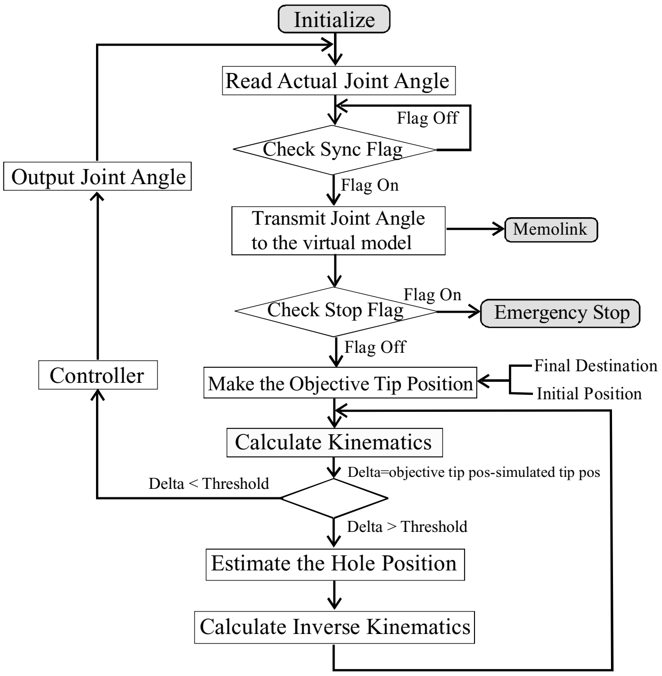

Fig. 6: Flow chart of AESOP control

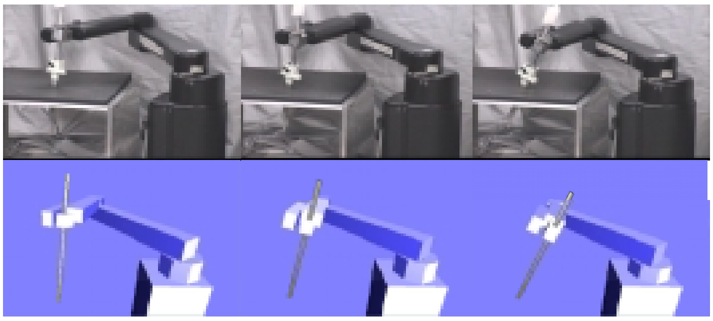

Fig. 7: Synchronization with the virual model

4 Avoidance of collision

To prevent a forceps from colliding with the organ or endoscopes, this system is constantly checking the distances between objects. For the computation of the distances, we adopted the PQP, the Proximity Query Package[10]. PQP is a geometric computation library for proximity queries performed on polyhedrons composed of numerous triangles. The functions of this package provide distance computation and tolerance check. The function of distance computation returns the distance between two models and the points established the minimum distance for the models. The function of tolerance check can detect whether two models are closer or farther than a tolerance value, and it compute more quickly than distance computation. Therefore, the tolerance check is usually used in normal mode.

Fig.8 shows the warning window for the surgeons to avoid collision. All surgical instruments and scanned 3D shapes are modeled on VRML 2.0 and the scenery is drawn using OpenGL. If the distance between two objects are closer than the critical distance, it warns surgeons by changing background color and popping up a warning message. This enables the slave robot to be stopped in case of emergency, even in the situation that surgeons don't notice the closeness. For the navigation to avoid collision, it can also show the shortest path between the closest points by changing the query type of PQP to distance computation mode.

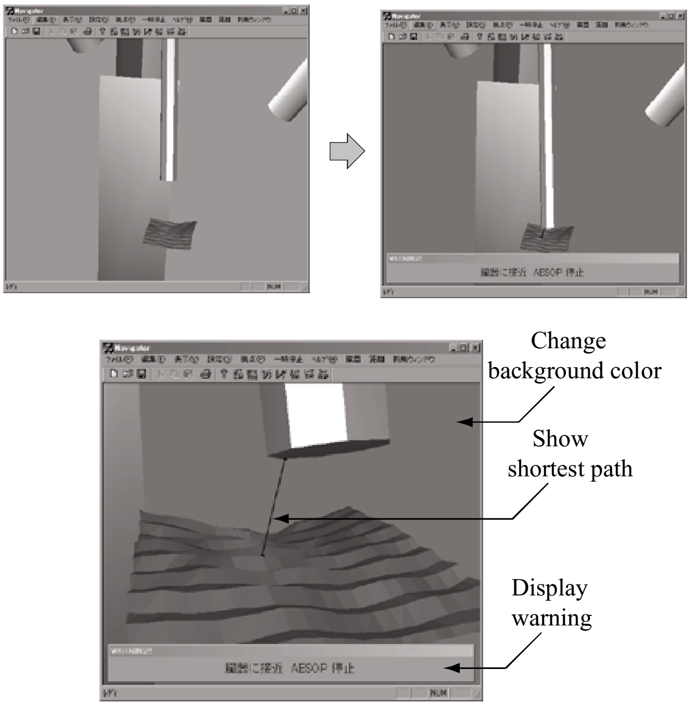

Fig. 8: Warning window for the surgeons to avoid collision

5 Experiment

5.1 3D Pointing Interface

In the current endoscopic surgery, surgeons have to mentally extract necessary information from the image of endoscope. In other words, they must judge the distance and the size of object using their sense. The surgeons would feel less tired if they were released from the mental load.

The 3D pointing interface works as follows:
(1) the surgeon toughes the screen of endoscopic image at a point of interest.
(2) the laser marker is controlled using the galvano scanner so that its position in the endoscopic image converges to the point of interest.
(3) Once converged, the 3D coordinates in the camera frame of the point of reference are recovered.
We tested the interface and measurements in in-vivo experiments on the liver of a pig. This system could provide the surgeon with the 3D coordinates of the point of interest in real-time. The response time from the touch on screen to the output of 3D coordinates was approximately 0.5 second. We will share the trace data that shows how the laser spot were controlled and converged to the target point on the liver. Fig.9 shows the trace of 3D coordinates while the laser marker converges to the point of reference on the liver of pig.

The touch screen interface assists a surgeon to intuitively indicate the point of interest on the 2D monitor screen (NTSC). The galvano scanner actively controls the laser spot inside the patient to locate it in the 2D monitor screen (NTSC) at the indicated point by the surgeon. And this system is realized by high speed tracking(955fps) and laser control using differential vector in the image. In every frame, differential vector between present laser point and destination is calculated. And laser beam is projected to the direction of the differential vector according to its size until the difference has turned into subthreshold.

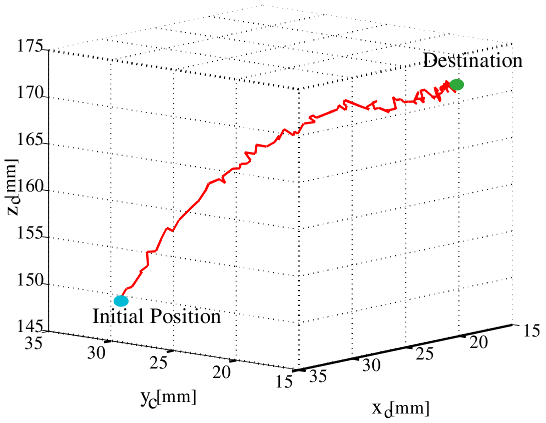

Fig. 9: The 3D trace of laser mark on the liver

5.2 3D Geometric Registration

We made an in-vivo experiment under the laparoscopy to obtain the intraoperative 3D geometry as shown in Fig.10. Even with the wet and shinny surface condition, it was possible to obtain the 3D positional data using a semiconductor laser light source. The laser power was 15mW. We scanned the area of 8cm square and obtained the 400 points data. Sampling time took 1.2ms for each point including the computaion for 3D position, and the total measuring time was 0.5 seconds. The intraoperative 3D geometry of the liver surface could be quickly obtained under laparoscopy as shown in Fig.11.

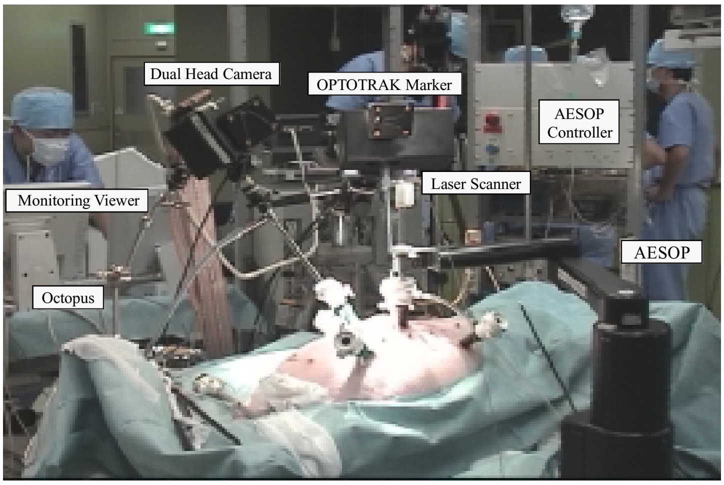

Fig. 10: The device settings in laparoscopic surgery

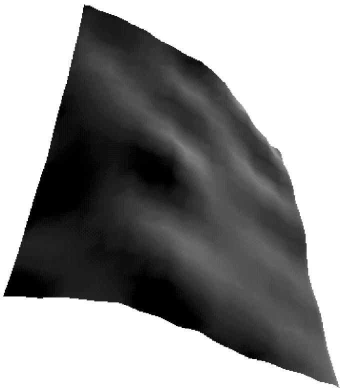

Fig. 11: 3D VRML image of liver in laparoscopy

5.3 Non-Master-Slave Operation

The present interface of surgical robot is limited to master-slave configuration. In the robotic telesurgery using master-slave, the large amount of image data must be transmitted through general network. It brings the difficulties of time delay. As the application of 3D pointing interface, the 3D position of destination for the surgical robot can be obtained from the 2D input on the touch screen.The surgeons have been able to guide the surgical robot to the place where it should approach at the end by the intuitive touch input on the endoscopic image. As shown in Fig.12, The forceps attached to surgical robot could be guided to the object by non-master-slave operation.

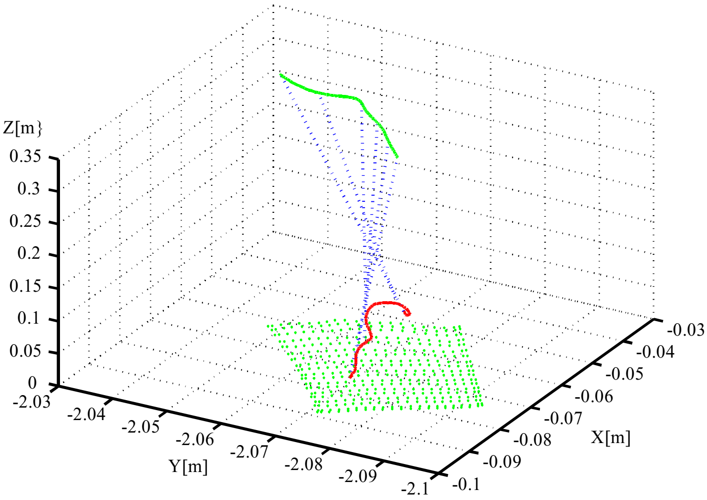

Fig. 12: The guided forceps by non-master-slave operation

5.4 Safety Management

Due to the narrow sight of the endoscope, the area which is able to be observed is limited for the surgeon. Therefore, it is easy to imagine the possibility of collisions between the organ and forceps of surgical robot in the out of view from endoscope. Here, 3D geometry of organ and surgical robot could be reproduced into the virtual space as shown in Fig.13. Surgeons will be able to figure out what happens in the out of view from endoscope by intraoperative monitoring. In the lab experiment, surgical robot could be stoped as emergency when the forceps approached against phantom organ within 10mm as shown in Fig.14. Fig.15 shows the minimum distance between forceps and phantom organ.

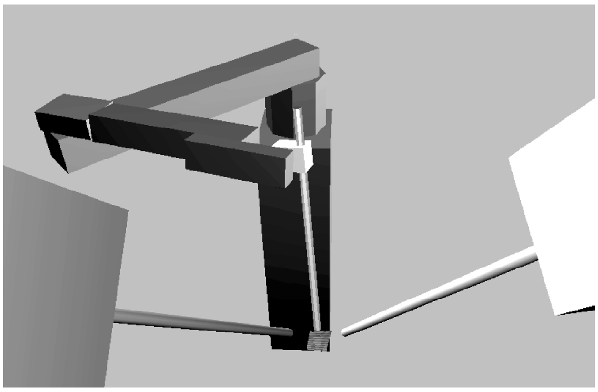

Fig. 13: Intraoperative monitoring

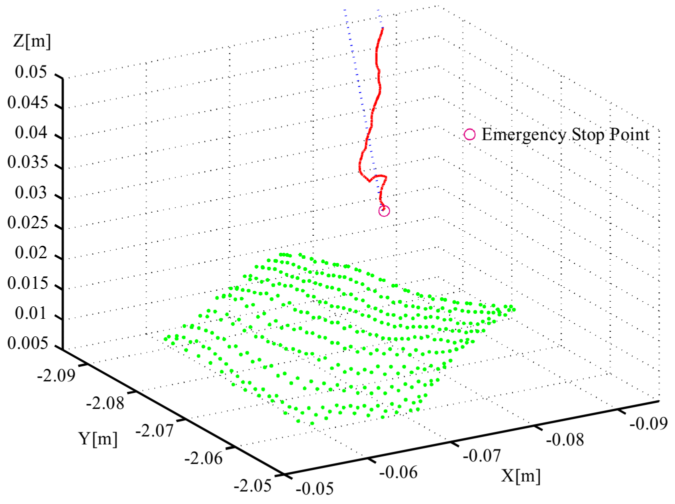

Fig. 14: Emergency stop usig intraoperative geometry

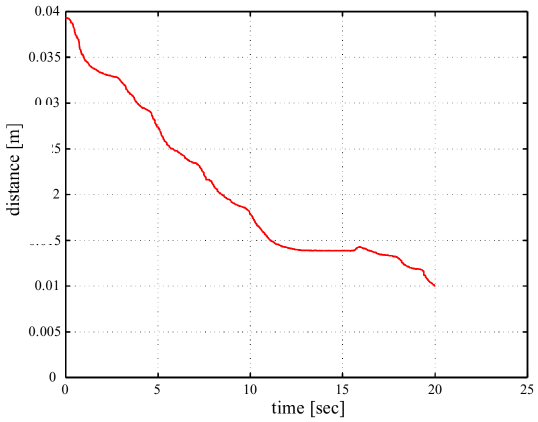

Fig. 15: The minimum distance between forceps and phantom organ

6 Conclusion

We developed the laser-pointing endoscope system. The intuitive interface to be an intraoperative support for surgeons was designed and fabricated using a touch screen and a high-speed camera. The intraoperative 3D geometric registration was realized under laparoscopic surgery. Preliminary results of in-vivo experiments verified the functionality and showed the performance. We proposed and realized non-master-slave operation for the surgical robot. Safety management was carried out using intraoperative monitoring in the virtual space.

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