Modular Design of Master-Slave Surgical Robotic System with Reliable Real-Time Control Performance *

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***Abstract*— This paper describes a master-slave surgical robotic system with software modular system design, which integrates various independently developed surgical devices. When we add new functions to the developed modular system, there is no need for time-consuming redesign of the entire system. However, we cannot evaluate the computational system load exactly because the system configuration changes according to the components included. A master-slave system should be a stable and reliable control system with high sampling frequency to enable human visual feedback control. Moreover, it requires consistent master-slave operation on the integrated component. To maintain reliable real-time performance and consistent operation, even with changes in system configuration, we introduced a software system consisting of; A position registration system to realize consistent operation on the integrated component, modular asynchronous system to avoid performance changes caused by the introduction of various subsystems and a management system to arbitrate inconsistencies between systems. An optical tracking system is used to integrate position and motion information of the subsystems to simplify setup in an operating theater. We evaluated the feasibility of the modular master-slave system by integrating independently developed components into the system. The results of the evaluation experiments showed that we could control all the subsystems consistently as an entire master-slave surgical system on an integrated coordinate system with stable real-time response.**

***Index Terms*— master-slave system, minimal invasive surgery, medical robot, modular system and real-time system.**

I. INTRODUCTION

Master-slave surgical robotic systems have been widely studied and developed ([1]-[3]). A master-slave system consists of a master arm system (master) and a slave manipulator system (slave). The slave manipulator system usually has three arms. The central arm holds an endoscope, and the two outer arms hold surgical instruments. During surgery, the surgeon can control either the central arm, to change the direction of viewing, or the two outer arms for manipulation. Together they produce high-quality precise operations that could not be performed using conventional surgical instruments. For example, da Vinci [4] has clinically applied one of these systems to thoracic and laparoscopic surgery. Master-slave robotic systems are usually a monolithic software system, which consists of several closely related components [5]. It can manage all the tasks and keep performance of the whole system simply because a monolithic system confines integration to specialized components in system development. However, replacement of even a single device requires time-consuming redesign of the whole system. On the other hand, modular system architecture consists of independently developed software components by which the developed system achieves various functions by changing components and thereby resolves the reprogramming problem. However, it is difficult to evaluate the computational system load when we change the system configuration depending on changes in the clinical requirements. In particular, a stable and reliable control system with high sampling frequency is required for a real-time surgical mechatronic system, such as a master-slave surgical robot. Nevertheless, it is desirable to realize various functions for sophisticated operations in an actual clinical environment. There is a trade off between these two requirements. To realize a modular master-slave surgical robotics system, while maintaining reliable real-time control, a new approach for control system design is required. This paper describes the design and implementation of a new modular master-slave robotic system with reliable real-time control, even with changes in system configuration, and the results of experiments to evaluate the utility and performance of this master-slave manipulator system.

II. METHOD

A. System overview

We have developed a modular master-slave manipulator system with various high-efficiency surgical tools for laparoscopic surgery ([6]). The system consists of the following components (Fig.1(a)(b)).

1) A robotic wide-angle view endoscope using wedge prisms [7]: We have developed a robotic wide-angle view endoscope using wedge prisms, which can observe a wide surgical field without moving or bending the laparoscope (Fig.1(c)). This was developed independently as a stand-alone surgical instrument; an embedded micro computer independently controls this robotic endoscope. The moving direction of endoscopic view is defined in laparoscopic coordinates. It receives remote command for view angle

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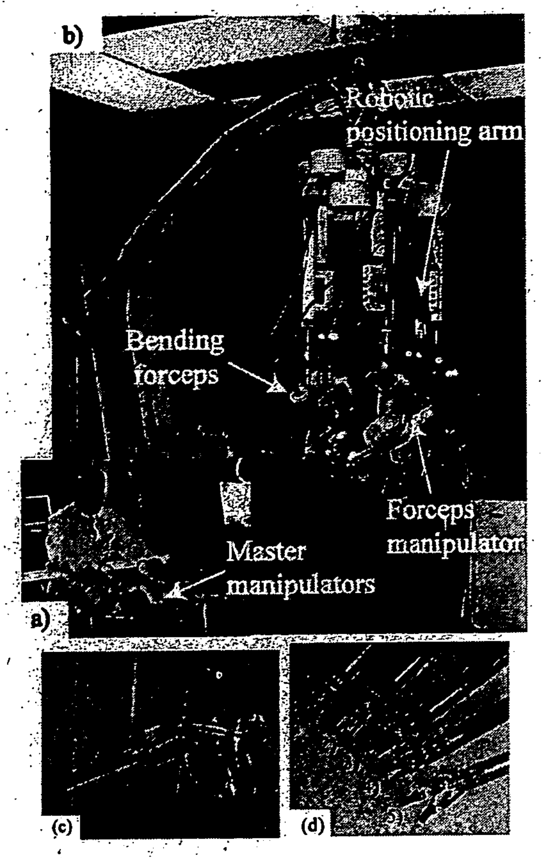

Fig. 1. Overview of the master-slave system: The master-slave system consists of a master(a) and a slave(b). The master consists of two positioning manipulators(right and left) for sensing surgeons' operation, footswitches and a monitor that shows an endoscopic image. The slave consists of the robotic positioning arm, a forceps manipulator, bending forceps and the variable view angle endoscope. The manipulator-positioning arm has six degrees of freedom (DOF). Each DOF is moved by a passive driving mechanism without actuators. The surgeon can set the forceps manipulator to the position appropriate for each operation using this robotic positioning arm. (c) Endoscopic manipulator; A robotic wide-angle view endoscope using wedge prisms, which can be used to observe a wide area without moving or bending the laparoscope, (d) Various surgical instruments of the forceps, 1) grasping forceps ,2)grasping forceps for soft tissue, 3),4)needle holder, and 5)electric cautery.

change described in the laparoscopic coordinates through RS232C communication interface. Direction of the optical axis of the endoscope relative to the origin set at the the robotic endoscope body was calculated by the micro computer. This information was transmitted to the other system through RS232C communication interface. Collision problem between manipulators is serious problem when a number of slave manipulators with large work space are used. Since the body of the robotic endoscope does not move, the use of this robotic wide-angle view endoscope using wedge prisms reduces the risk of collision of manipulators.

2) Forceps manipulator: The forceps manipulator has four degrees of freedom (DOFs) to create the same motion of the forceps as in conventional laparoscopic surgery, two DOFs for orientation around the incision hole, and two DOFs for insertion and rotation of the forceps[6].

3) Bending forceps: We manufactured various types of instruments; two types of needle holder, grasping forceps, and special grasping forceps for soft tissue, such as intestines (Fig.1(d))[6][8].

B. System configuration

Therefore, our modular master-slave manipulator system consists of various independently developed surgical devices. While integrating components with individual different sampling frequencies in modular manner, the master-slave system must be a stable and reliable control system with high control sampling frequency, at least 100 ms to allow human visual feedback control. The consistent master-slave operation in coordinates associated with changes in the endoscopic view is also required. In addition, in clinical situation, it is possible that some of the surgical devices are interchanged with different surgical devices. Reliable real-time performance and consistent operation should be maintained, even with changes in system configuration. To meet these requirements, we proposed a new system configuration with the following three-major functional systems:

- Position registration system to achieve consistent operation in the integrated coordinate system,
- Modular system with asynchronous capabilities to avoid performance changes caused by the introduction of various subsystems in an individual control interval,
- Management system to arbitrate inconsistencies between systems and to maintain consistent performance in the entire system.

These systems are described in detail in the following sections.

C. Position Registration System

If we use various surgical tools at the same time, it is required to measure the various positions and orientations of the instruments (Fig.2). An external measurement sensor, such as an optical tracking sensor, is effective in achieving the above requirements because it can be selected independently, regardless of the features of the integrated surgical tools. An alternative method for measuring the position of each subcomponent is the use of mechanical sensors, such as rotary encoders and potentiometers, installed in the mechanical arms. The measurement area of the mechanical sensors is confined to the working space of the robotic mechanical arms and the additional electrical wiring makes the system more bulky. Consequently, we used an optical tracking sensor ($POLARISR^R$, Northern Digital Inc. Canada) as an external measurement sensor. Optical markers were mounted at the base of each device and the sensing unit that emitted infrared light and received reflected light from the markers tracked them. A root mean square (RMS) error of approximately 0.35mm has been achieved. The sampling interval is approximately 50 ms. In master-slave operation, surgeons operate based on the endoscopic view at the master site and send the command to the slave.

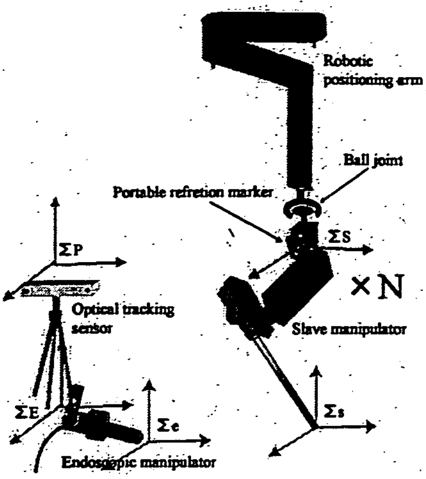

Fig. 2. Coordinates of each surgical instrument and optical tracking sensor: There are various coordinates in a modular master-slave system; coordinate of an optical tracking sensor:(ΣP), coordinate of an end of endoscopic manipulator:(ΣE), coordinate of an endoscopic view:(Σe), coordinate of an end of slave manipulator:(ΣS), coordinate of a tip of slave manipulator:Σs and coordinate of a master manipulator:ΣM

At the slave site, this command based on the coordinate of endoscopic view is transformed to the coordinate of the slave robotic manipulator. A slave manipulator follows the coordinates associated with changes in the endoscopic view when operated in the master-slave mode. In summary, coordinate translation flow in master-slave operation is as shown in Fig.3.

D. Modular system with asynchronous and periodic response

Generally, communication between subsystems is realized by synchronous operations. Using synchronous operations suspends one process until another process finishes to maintain the consistency of communication data between subsystems. On the other hand, it makes the performance of one process unreliable, because their intended individual performance changes. Considering master-slave operation required real time performance, this method is not effective. Therefore, we selected asynchronous communication to keep the performance of subsystems with individual sampling frequency. Using an asynchronous communication means that the integrated subsystems can be used at their intended individual performance independent of the others, avoiding interference between integrated modules. This method simply makes each subsystem take most up-to-date sampling data. Therefore, in the system control software, each device's control software is executed as an independent process and communicates by using shared memory. This achieves safe and quick removal of any of the integrated surgical devices from the entire system during a surgical operation, because each process executes individually. The functions above serve a large-scale system consisting of various components, such our modular system, with safety. Moreover, considering a master-slave system required real-time operation, all the subsystem should be execute at constant period with reliable performance. If we use general Operating System(OS) such as Windows and Linux, the performance of each subsystem is determined by OS at random. It causes jitter of execution period and does not prohibit our system from keeping the reliable real-time performance. We must confidently expect the next execution period of each subsystem to be without jitter for a real-time surgical mechatronic system, such as a master-slave surgical robot. To meet the condition, the subsystems should have sufficient performance to guarantee adequate execution of the required tasks. Real-time periodic execution and CPU reservation is guaranteed using functions of the real-time operating system (OS) (Time Sys Linux, Tims Sys Corp, USA). This keeps the performance of the surgical modules sufficiently reliable to control each subsystem. Therefore, we developed the modular system shown in Fig.4 with asynchronous communication and periodic execution using a real-time OS.

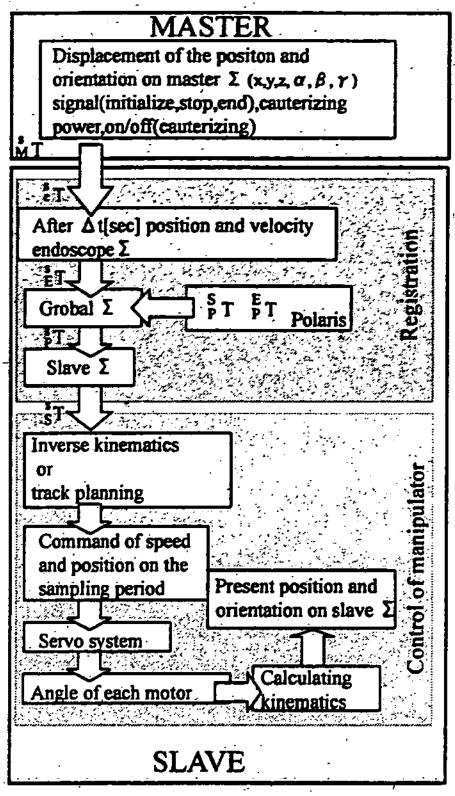

Fig. 3. Data flow in master-slave operation; Surgeons operate based on the endoscopic view at the master site and send the command to slave(${}^{s}_{M}T$). Therefore, the command based on the coordinate at the master site was translated to the coordinate of endoscopic view(${}^{s}_{e}T$). At the slave site, this command based on the coordinate of endoscopic view(${}^{s}_{e}T$) was translated to the coordinate of slave robotic manipulator(${}^{s}_{S}T$) by way of polaris coordinate(ΣP).

E. Management system

The position registration system follows a series of process, as shown Fig.??. Consistent master-slave operation on

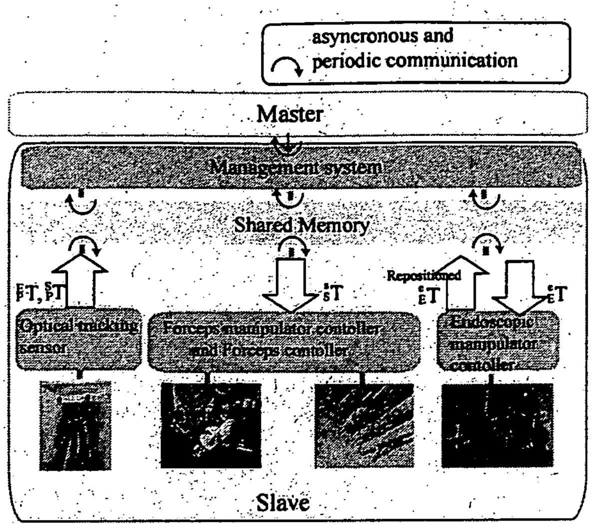

Fig. 4. System architecture of a management system consisted of a various components: Communication between components and a management system is asynchronous communication by using Shared Memory. We used real-time OS to keep performance of integrated devices reliable. Using real-time periodic function enabled each component to execute at a constant period.

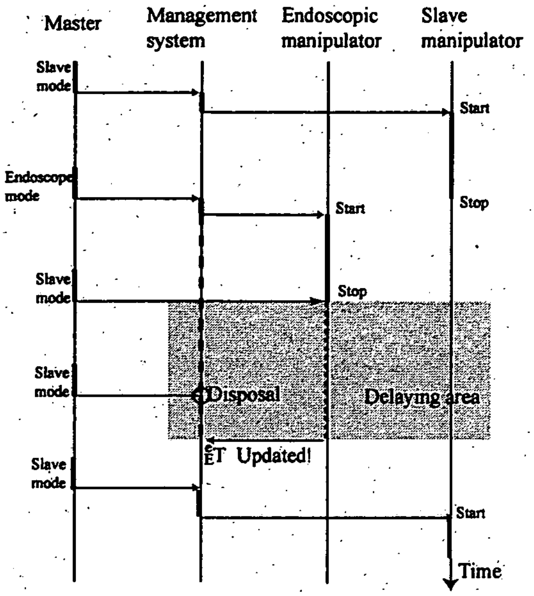

Fig. 5. Overview of data exchange among master, management system, endoscopic manipulator and slave manipulator

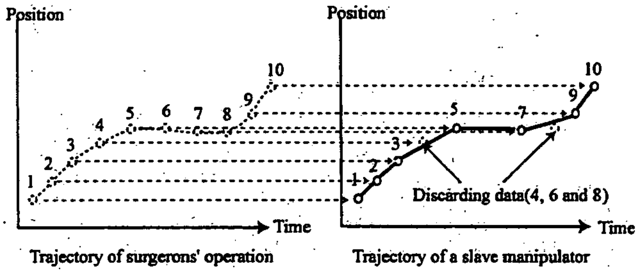

Fig. 6. The trajectory of the slave from the last command sensed and the newest one after discarding operation: Dashed line is trajectory of sensing surgeon's operation, continuous line is actual driving trajectory of a slave manipulator and white circle is position data with time-stamp from 1 to 10.

the coordinates associated with changes in the endoscopic view cannot be achieved unless position registration follows the proper procedures in the correct order. One of the solutions of achieving consistency in following the proper procedures in the correct order is to use a synchronous communication system. However, this method changes the intended individual control. Therefore, we adopt asynchronous communication to keep real time performance. With this system configuration, it is not possible to follow proper registration procedures and achieve the consistent operation associated with position registration. This is because this method such as just picking up most up-to-date communication data, do not guarantee the correct order. Nevertheless, we must achieve the position registration by flowing the proper procedures with asynchronous operation. Moreover, master and slave are connected by Ethernet connection using TCP/IP communication. Then, an unexpected jitter caused by an internet connection may not guarantee reliable performance in the entire system. We included the following arbitration functions to avoid thease situation.

- Arbitration between subcomponents: To realize synchronize operation between subsystems, regardless of asynchronous manner,
- Arbitration between master and slave: To maintain real-time performance between subsystems, regardless of jitter.

1) Arbitaration among subcomponents: A slave manipulator follows the coordinates associated with changes in the endoscopic view when operated in master-slave mode. The slave manipulator must therefore acquire the new coordinates after each change in the endoscopic view. In our endoscopic manipulator it required approximately 250 ms to acquire the repositioned coordinates after endoscopic view change whereas communication interval between master and slave was 100 ms. Because of the independent operation of each subsystem with its specific periodic execution schedule, if the slave manipulator moves before acquiring the new coordinates, its movement may be incorrect.

The management system avoids this possibility by filtering the motion commands from the master. When a command for endoscopic view change is issued from the master manipulator system, the management systems starts to dispose the motion commands for the slave manipulator until the new endoscopic coordinates are established and its data are sent from the endoscope. This ensures that the slave manipulator cannot move, however, an operator can control the slave by communicating with the master at fixed clock periods, regardless the condition of the slave system. Once this registration is reestablished, the slave manipulator starts to follow the motion commands from the master manipulator(Fig.5).

2) Arbitaration between master and slave: Internet connection is possible to cause unexpected communication frequency between subsystems. Another possible failure can occur when displacement requests from the master arrive at a faster rate than they can be executed by the management system. The requests are accumulated over short periods with the system time and stored for subsequent execution leading to unexpected delayed motion of the slave manipulator. In some cases, a flood of required operations may cause loss of control of the slave manipulator. To avoid this problem, we used the system time information to identify the most up-to-date request from the master discarding commands that cannot be handled by the slave manipulator. Generally speaking, a high rate of position command transmission is required to achieve a precise continuous path control of the slave manipulator. Point-to-Point (PTP) control is also important to achieve precise positioning of the surgical device. That is, using the system time information the management system interprets the series of positioning commands from the master into a series of commands that can be handled by the slave manipulator. With this command interpretation, the slave manipulator approximately follows the positioning commands from the master as precisely as possible with stability(Fig.6).

III. EXPERIMENTS AND RESULTS

Experiments were conducted to evaluate the basic performance of the proposed modular master-slave surgical robotic system.

A. Evaluation of Registration

We evaluated position registration system in the master slave surgical manipulator as shown in Fig.1. We prepared a task requiring position registration of submodules and complicated manipulation. The task was performed using color cones (diameter approximately 10 mm, height approximately 20 mm) placed at random(Fig.7). An operator at the master site controlled the slave manipulator using the coordinates of the endoscopic video image. The operators were two engineers engaged in the development of the master-slave system and one volunteer that was not accustomed to master-slave operation. The operator was requested to move a ring (diameter approximately 15 mm) from one cone to another. Ease of operation was evaluated by measuring the operation time, defined as time from holding the ring to completion of the move. The measurement was repeated three times for each operator. Table 1 shows that the engineers have better results than the volunteer for operating speed but all standard deviations were similar. It appears that differences in experience of master-slave operation were the main factor in the varying operating time results. The small standard deviation of operating time for each operator indicated that operationality changed little for each subject among trials and stable manipulation was achieved in this system. These results showed that registration and consistent placement on a common coordinate were achieved.

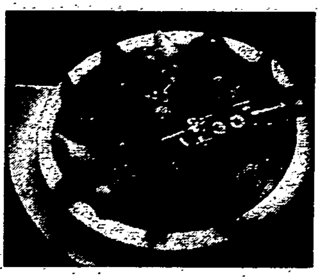

Fig. 7. Experimental environment: As one example of dexterious task without registration, we prepared some color cones (diamater is about 10mm, height is about 20mm) placed at random.

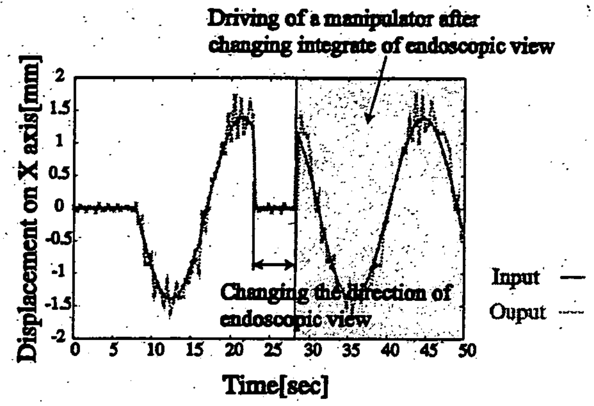

Fig. 8. Experimental results showing the movement of a manipulator in X coordinates:

B. Evaluation experiment of the management system

In this experiment, we used various surgical devices, as described in the system overview, and tested the capability of our open, modular system to perform as a master-slave system using the management system, even if the integrated surgical device was independently developed and was not designed to be a slave device.

1) Evaluation of arbitaration among subcomponents: We attached optical tracking markers to the tip and the base of the slave manipulator and measured the positions of these markers using the optical tracking sensor. We simulated a sequence of endoscopic coordinates on a computer (the Virtual Master), sent this sequence from master to slave using TCP/IP networking at 100 ms and evaluated whether state change was conducted smoothly in two different modes (slave mode for driving slave manipulators and endoscope mode for driving the endoscopic manipulators). Figure.8 shows that the driving trajectory (displacement distance) of slave manipulator followed the input data after changing the mode from endoscope mode to slave mode. The result in endoscope mode showed approximately 0. This is why the endoscopic manipulator only drives and then the slave manipulator

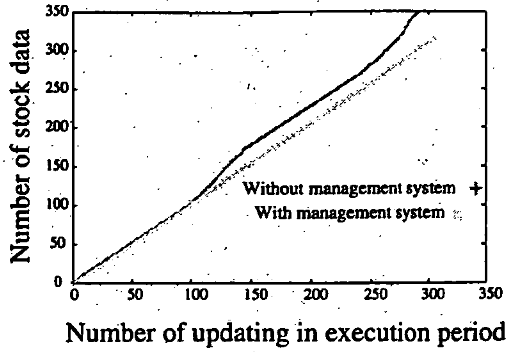

Fig. 9. Comparison result with and without the management system; This Figure was that the result of data communication by the slave manipulator control system from the master system.

stops in endoscope mode. There is a fructuation of the slave manululator motion data in Figure. 8, it is mainly caused by the measurement errors of the optical tacking sensor(RMS approximately 0.35mm). Although it took 250 msec for the robotic endscope to update the endoscope coordinates system after it changes its direction of view, the management system could successfully arbitrate the transition of the old coordinates system to the new system by suspending the slave manipulator motion for approximately 300 msec. The updating period between master and slave was kept as 100 ms. This data showed that the system successfully suspended the operation of the slave manipulator during new endoscopic coordinate acquisition and restarted its motion after registering the subsystems using the new endoscopic coordinates. In this experiment, the communication to acquire coordinates from the endoscope was slower than the communication between master and slave manipulators. Even under this condition, our management system could operate surgical devices at their individual control intervals.

2) Evaluation of arbitaration between master and slave: This experimental condition was the same as that above. Fig. 9 shows the number of data stock by the slave manipulator control system from the master system. Without this arbitration, a flood of required operations may causes loss of control the slave manipulator. Even if an operator wants to stop immediately, the stop motion required emergency will be executed after some delay. Introduction of the proposed management system stabilized data acquisition required real-time performance between master and the other subsystems.

IV. DISCUSSION

Many telerobotic systems with distributed modular architecture using standard middleware software have been developed. Several studies using surgical robotic systems have been reported using the common object request broker architecture (CORBA), which is one of the many standard middleware software packages available. CORBA allows us to integrate various systems in a transparent manner, regardless of the hardware, operating system, or programming language used. The application of a CORBA-based system to control an image guided surgical robot has been reported [9,10]. Schorr et al. controlled an MRI compatible biopsy robot by sending its control information using CORBA. Considering the nature of an MRI scanner, it appears that the required bandwidth for communicating navigation data in that case is not as high as the bandwidth requirements for communicating between our master arms and slave manipulators or for the dynamic motion control of our robotic manipulators. These applications require relatively slow response of the subsystems because the manipulator was controlled by a surgical navigation system without human interference. The command updating frequency was relatively low and did not require real-time operation. When we implement a master-slave system that requires strict real-time operation, such as a manipulator controller, then these non-real-time objects can create a bottleneck that will determine the overall system performance. The introduction of surgical navigation in the operation of a master slave manipulator is required to achieve safe and more accurate surgical operation. CORBA uses a communication protocol based on TCP/IP, which is unpredictable for sending control commands. Therefore, it is difficult to realize a master-slave system requiring strict real-time operation. To implement a more sophisticated surgical robotic system, such as a master slave surgical manipulator system, with surgical navigation, a method must be developed to keep satisfactory, stable overall system performance while enabling the integration of various subsystems. Our modular system with the combination of asynchronous communication and real-time periodic execution can integrate various surgical devices without changing the intended performance of each subsystem and control processes with a real-time OS, although our modular design cannot provide some of the advantages of CORBA, such as connection in a transparent manner, independence from the operating system. Introduction of the proposed management system and enabled various integrated surgical devices and their control process to be executed as in synchronous system with no interferences. In addition, it can stabilize data communication between master and slave using asynchronous communication between the other subsystems. We implemented position registration of various surgical instruments using an optical tracking system by the system design approach described above. We could control all the subsystems in a consistent manner as an entire master-slave surgical system on an integrated coordinate system with stable real-time response.

V. CONCLUSION

In this paper, we describe a modular master-slave surgical robotics system, which maintains reliability in real-time control. We propose three design principles; a position registration system for achieving consistent operation between surgical instruments, an asynchronous communication system to avoid interference between modular subsystems and the management system to keep the whole system synchronized. We confirmed our methods through evaluation experiments and described the difficulty of applying CORBA to master-slave systems. Position registration of various surgical instruments using an optical tracking system was achieved. A task requiring, complicated manipulation without position registration, was performed. The standard deviation of operation time was small and stable manipulation for each operator was indicated. We integrated a robotic wide-angle view endoscope using wedge prisms that has relatively slow communication capabilities. Our management system allowed the integration of such devices with different performance. We could control all the subsystems consistently as an entire master-slave surgical system on an integrated coordinate system with stable real-time response. Future developments will include the incorporation of additional forms of surgical devices to improve the safety and accuracy of surgical procedures.

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A Novel Robotic Laser Ablation System for Precision Neurosurgery with Intraoperative 5-ALA-Induced PpIX Fluorescence Detection

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Abstract. We developed a combined system of tumor detection by 5-ALA-induced PpIX fluorescence and precise ablation by micro laser for the first time, with an automatic focusing and robotic scanning mechanism for the brain surface. 5-ALA accumulates on tumors to be metabolized to become PpIX that is a fluorescent. Intra-operative detection of 5-ALA induced PpIX fluorescence provides useful information for tumor detection. The wavelength of the micro laser is 2.8 μm close to the absorption band of water. This laser is effective only on the surface of brain tissue, enabling precise ablation at the boundary between tumor and normal tissue identified by intra-operative 5-ALA induced fluorescence. Combination tests of the fluorescence measurement and the laser ablation were performed, and it was possible to extract the area with fluorescence appropriately from the measurement data, and the micro laser with automatically scanning selectively ablated the extracted area.

1 Introduction

In current neurosurgical practice, surgeons can remove most of a tumor with an accuracy of a few millimeters by using a combination of conventional surgical instruments, such as an electric cautery, and a computer-aided navigation system based on diagnostic images, such as MR and CT images. Residual tumor, especially if the malignant tumor like glioma, may impair the prognosis of the patients and it is necessary to remove as much of the tumor as possible while keeping the normal tissue

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intact. However, it is difficult to know the exact boundary between tumor and normal tissue, and excessive ablation of the normal brain tissue will damage its function.

In craniotomy procedure, deformation of the brain tissue, called "brain shift", occurs due to cerebrospinal fluid leakage and surgical interventions. In some cases, brain shift reaches to several tens of millimeters and continuously increases during the procedure [1]. This requires navigation based on intraoperative MR images. This navigation, however, contains a few millimeters of errors at a maximum caused by a registration of preoperative diagnosis images [1] and intraoperatiove images and an accuracy of the position tracking using such as an optical marker. Furthermore, there is a tradeoff between high frequency of image acquisition for more accurate navigation and not time-consuming imaging.

Similarly, the accuracy of conventional surgical procedures is a few millimeters for removal of residual tumors. Therefore, we desired to achieve a more precise operation with an accuracy of sub-millimeters. To that end, each of a measurement and removal of residual tumors has to realize this accuracy.

To solve these problems, we have proposed a novel approach to therapy using 5-aminolevulinic acid (5-ALA) [2][3] and a micro-laser ablation system [4], with the boundary between the tumor and the normal tissue distinguished by the 5-ALA-induced protoporphyrin IX (PpIX) fluorescence in the tumor and with accurate ablation of the tumor with the micro laser. 5-ALA, which is orally administrated to a patient, accumulates on tumors to be metabolized to become PpIX that is a fluorescent substance [5]. The wavelength of the micro laser is 2.8 μm. Light with this wavelength is mostly absorbed by water, and therefore this laser is effective only on the surface of brain tissue, enabling precise ablation at the boundary between tumor and normal tissue [4].

In this paper, we developed a combined system of tumor detection using 5-ALA and precise ablation by micro laser, with an automatic focusing (AF) and robotic scanning mechanism for the brain surface. This system is designed for possible localized pinpoint detection of the tumor, then ablating the fluorescent area with stepping driven precise position control in the whole system. This is first attempt to integrate intraoperative fluorescence detection and high precision laser ablation system. In addition, each of the measurement and ablation is performed under the robotic position controlling.

2 Materials and Methods

In this chapter, the tumor detection using 5-ALA-induced PpIX fluorescence, the micro laser module, the automatic focusing and robotic scanning system, and the whole system integration are described. Finally we proposed the experimental procedure for combining these surgical processes.

2.1 Intraoperative Detection System for Brain Tumor Using 5-ALA

Fluorescence of PpIX is fully observed a few hours after orally administrated 5-ALA. Irradiating near-ultraviolet light of around 400 nm, PpIX emits the fluorescence of the wavelength of 635 nm at peak intensity from the brain tissue.

Applying a highly sensitive camera is one of the reasonable ways for intraoperative detection of PpIX fluorescence. Although it is possible to acquire a wide-area 2-dimensional data at one time, obtained data contains only light intensity and simple color information. As PpIX fluorescence is so much weaker than the excitation light and a guide laser of the AF system, it requires the optical narrow-band-pass filter to cut off the other light sources. Nevertheless, it is difficult to separate the fluorescent component from the intensity and the color information of the image signal. Therefore, we chose the use of a spectral photometer, easily extracting the peak intensity of the fluorescence. The spectral data contains important information about tumors; for example, a spectral shape and a peak wavelength possibly vary with a density of tumor cells, a class of tumors, and other conditions of tissues. In the future task, we consider acquisitions of the functional information of tumors by spectral analysis.

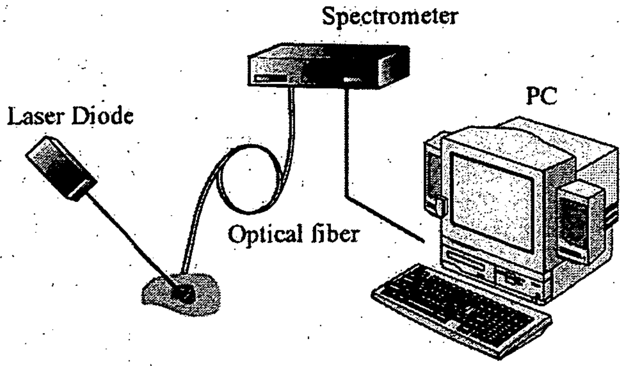

Fig. 1. Tumor detection system using 5-ALA-induces PpIX fluorescence

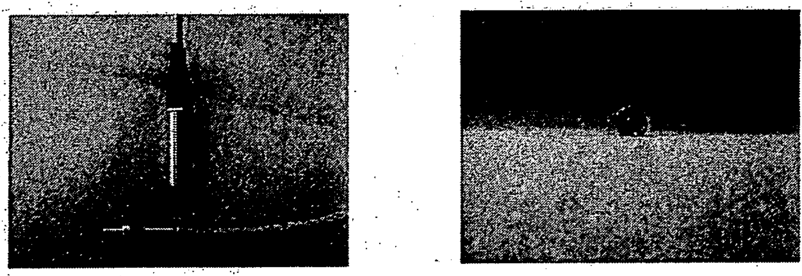

Fig. 2. Fluorescence detection probe

PpIX fluorescence was collected by a detection probe and guided into a spectrophotometer through an optical single-mode fiber, then performed spectral analysis (Fig. 1). The detector has a diameter of 8 mm, using aspheric lenses to correct aberrations. The detection resolution is set to 0.6 mm, considering a tradeoff between not decreasing of the acquired light intensity in proportion to the square of the resolution diameter and improving the accuracy of the measurement (Fig.2). A band-pass filter, which transmits over 60 % at 635 nm and up to 5 % at 670 nm, was fixed on the tip of the detector, cutting off the excitation light and the guide laser (peak at 670 nm) of the AF system. The working distance of the detector is 16 mm to a tolerance of plus or minus 0.5 mm.

2.2 Micro Ablation Laser Module

For ablation of tumor tissues, we used a mid-infrared continuous-wave laser with a wavelength of 2.8 µm, being output by a microchip solid-state laser on the tip of a laser probe [4]. The pumping light source for the solid-state laser is a near-infrared diode laser with a wavelength of 970 nm, guided through a quartz optical fiber to the laser probe.

As the light wavelength around 3µm has strong absorption feature by water, this laser is effective only on the surface of the living tissue, and it can make a precise ablation with a low output of 0.2 W or less. The laser beam is focused to a diameter of 0.1 to 0.15 mm with a lens, and an ablation groove is formed equivalent to the spot diameter in the soft vital tissue. The working distance of the laser probe is 15 mm ± 1 mm.

2.3 Automatic Focusing and Robotic Scanning System

Both the fluorescence detection probe and the micro laser probe have each working distance, and this requires an AF mechanism, constantly maintaining the distance from the brain surface. In this practice, we used an AF system designed based on the three-dimensional measurement system (Mitaka Ko-ki Co., Ltd.) (Fig. 3). In this system, position measurement was performed using a confocal optical mechanism and the guide laser was picked up with a split photodiode, enabling a focusing with an accuracy of micrometers. The wavelength of the guide laser is 670 nm. This system was coupled with 2-axial automatic stepping drive stage and can make a robotic scanning on the surface of the brain.

Fig. 3. Automatic focusing and robotic scanning system

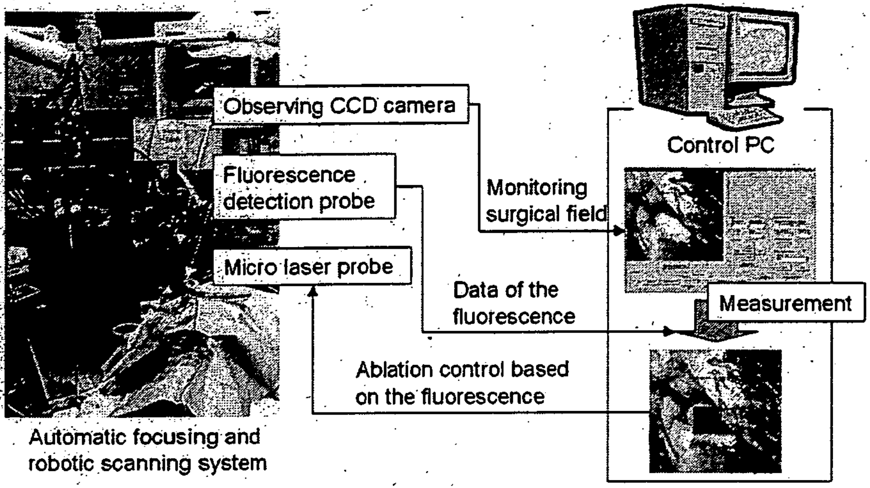

Fig. 4. System configuration

2.4 System Integration

Fig. 4 shows the system configuration in this paper. The fluorescence detection probe and the micro laser probe were attached to the AF system. The data from the spectral photometer was stored into a personal computer (PC). Switching of the micro laser and scanning with the stepping drive were both controlled by the PC. We can observe surgical field view by a CCD camera in the AF system. This image was used to control electric motors to position the fluorescence measurement system and the laser ablation system.

2.5 Experimental Procedure

Measurement of Fluorescence Signal

Measurement area was defined on a CCD camera view of the AF system and sectioned in a grid pattern. Measurement was performed on each grip point with raster

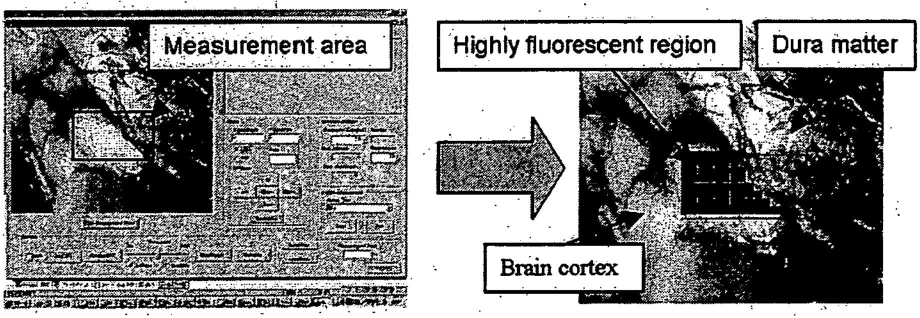

Fig. 5. An example of the measurement procedure of the fluorescence on a porcine brain

scanning. A point in the measurement area was regarded to have same fluorescent property with nearest grid point. A grid interval was determined to 0.4 mm, considering that the grid square was included in the circle of the measurement resolution of 0.6 mm. As a measurement required more than a few hundred of milliseconds, it took several tens of seconds or more to measure a few millimeters square. Fig. 5 shows an example of the fluorescence measurement procedure.

Ablation of the Target Area

A threshold was set for the intensity level of measured fluorescence. In this paper, a surgeon or an experimenter determined the threshold, viewing the measurement area on the CCD camera image. Then scanning was started, and the micro laser was automatically irradiated on the region over the threshold.

3 Results

Combination tests of the tumor detection system and the micro ablation laser module were performed for a biomedical simulant material (phantom) and a porcine brain.

3.1 Phantom Experiment

The phantom was composed of agar plate containing Intralipid-10% that is intravenous lipid emulsion and used for scattering medium [6]. The concentration of Intralipid-10% was adjusted so that the scattering coefficient became 3 cm^{-1}, which is similar to that of Glioma [6][7]. A half part of the phantom contained PpIX to emit fluorescence and the other half part did not contain PpIX.

Fig. 6(a) shows one of the results of experiments. Black rectangular area stands for the scanned area by the system. The system could identify the boundary between the area with fluorescence and without fluorescence, and could precisely ablate the fluorescent area with automatically scanning.

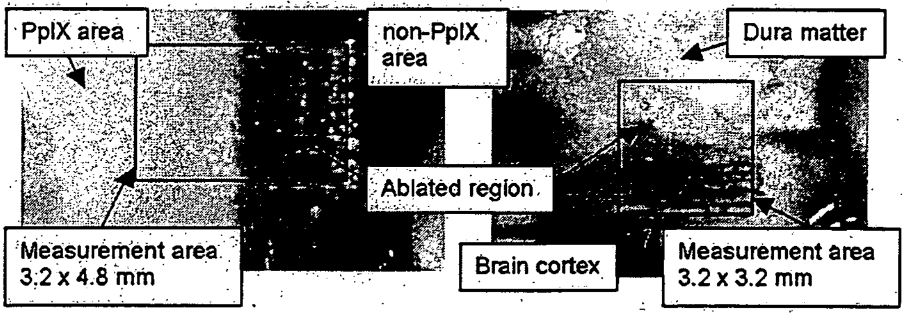

Fig. 6. Result of the combination tests of the tumor detection system and the micro ablation laser module

3.2 Porcine Brain Experiment

The target was the surface of a porcine brain exposed by craniotomy under anesthesia. Before the experiment, 5-ALA was administrated in sufficient quantities to accumulate on a normal brain tissue and metabolize to become PpIX. A half of the measurement area was covered with dura matter, where the fluorescence was not observed, and the other half was exposing brain cortex.

Fig. 6(b) shows one of the results of experiments. Black rectangular area stands for the scanned area by the system. The dura matter covering the porcine brain could not completely block the fluorescence. We could identify weak signal of fluorescence from some part of the dura matter. As shown in Fig. 6(b), ablation laser was irradiated to such area on the covered region. We could successfully identify and ablate the fluorescent area of the porcine brain based on the fluorescence data. The AF system functioned properly even for porcine brain and was effective to stabilize both of the conditions of the measurement and the laser ablation.

4 Discussion and Conclusions

We developed a combined system of tumor detection by 5-ALA-induced PpIX fluorescence and precise ablation by micro laser for the first time, with an automatic focusing and robotic scanning mechanism for the brain surface. In this system, ablation was performed based on the fluorescent information under the robotic position controlling.

Combination tests of the fluorescence measurement and the laser ablation were performed for a biomedical simulant material (phantom) and a porcine brain. Measurement areas of the phantom and the porcine brain were both separated into fluorescent part and non-fluorescent part. In each test, it was possible to extract the area with fluorescence appropriately from the measurement data, and the extracted area was selectively ablated by the micro laser with automatically scanning.

In this practice, the experimental targets were clearly separated into the area with fluorescence and without fluorescence. In clinical cases, the boundaries between tumors and normal tissues are often unclear, and tumors invade normal tissues. Therefore, thresholding of a fluorescence data and an extraction of the area for ablation will have problems, and are considered making some automation process. Solutions for these problems are desired in the future work. To automatically discriminate the tumor region by fluorescence data, a multiple classification analysis based on another spectral features not only peak intensity of the fluorescence will be investigated.

Acknowledgments

We wish to thank many people and groups who have contributed to this effort. Research on medical devices for analyzing, supporting and substituting the function of human body funded by Ministry of Health, Labour and Welfare.

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06(XIII)-96

脳神経外科手術における異種環境統合プラットフォームの開発と評価～第2報　オクルージョン問題の回避

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Abstract: We developed a cancer detection system using tumor-selective Protoporphyrin9 (Pp9) fluorescence by 5-Aminolevulinic acid for assisting intra-operative detection of brain tumor. It is required to integrate intra-operative information acquired from the cancer detection system and navigation information to realize more sophisticated navigation system. Therefore, we developed an integrated intra-operative information system that consistes of a navigation system, a cancer detection system and an optical tracking sensor. However, our developed system does not work if optical tracking system occurs occlusion. Therefore, we developed redundant position sensor system using multi optical tracking sensor to solve occlusion problem. Through an In vivo experiment, we confirmed this integrated system is effective in clinical use.

Key Words: Neurosurgery, System integration, optical tracking sensor, occlusion

1．背景

これまで本研究室では脳外科手術支援システムとして，5ALA 誘導 Pp9 蛍光から得られる蛍光強度・スペクトル情報を腫瘍の悪性度に関連付け，定量的に診断を行うための腫瘍同定システムの開発を行ってきた．このような腫瘍の悪性度などの情報が，ナビゲーション情報と共に術者に提示されることで，より効果的な手術ナビゲーションが実現できると考えられる．そこで我々は，蛍光計測装置に位置トラッキング用のマーカをとりつけ，計測した蛍光の強度・スペクトルを位置情報と対応づけを行い，ナビゲーション画面上に提示を行う情報統合システムの開発を行ってきた[1]．また，統合システムでは，位置情報の統一的な取り扱いが求められることから，光学式位置計測装置（POLARIS®, Northern Digital Inc.）を用いて，座標系の統合を行った．しかし，光学式位置計測装置は，他の位置計測装置と比較して計測精度の高い位置情報が得られる一方，測定範囲，方向に制限があり，またセンサが遮断されることによって計測不可能に陥る問題（以下：オクルージョン）がある．特に手術場では，外科医の他，サポートをする医師が，手術領域を頻繁に行き来するため，センサが遮断される場合がある．このとき，位置情報に対応付けられた計測情報が取得できず，ナビゲーションでの手術支援が行えなくなる．このオクルージョンの問題に対し，冗長となる位置計測装置を用意し，多方向から計測対象をモニタリングすることで解決する方法が提案されている[2]．冗長となる位置計測装置を用いることで，1台の計測が遮断された場合でも，計測可能な装置に切り替えることで，計測対象のオクルージョンの発生を抑えることができる．そこで本稿では，位置計測装置に冗長性を持たせ，オクルージョンが発生した場合においても，ナビゲーションによる手術支援が可能な統合手術支援システムの実装を行った．

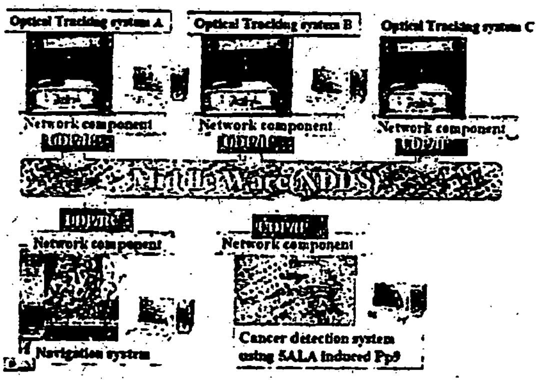

Fig.1 Integrated surgical robotic platform using NDDS

2. 方法

2.1　システム構成

統合手術支援システム(Fig.1)は，5ALA induced PpIX を用いた術中脳腫瘍蛍光診断による腫瘍同定システム，ナビゲーションシステム，冗長となる複数台の光学式位置計測システム，術中ログシステムにより構成される．各手術支援システムは，分散オブジェクト技術の1つである Network Data Delivery Service(NDDS)を用いて統合を行った．分散オブジェクト技術の利用は，OS

やプログラム言語，ハードウェアに依存しない，また各機器に対してシステム統合のための変更を最小限に抑える事が可能という特徴がある．これらのシステムはすべて，Internet Protocol(IP)に基づいたネットワークで接続されている．

2.2 冗長性のある位置計測装置を用いた計測方法

位置計測装置が提供する計測情報は，位置計測装置の設置された位置に基づいた計測情報であるため，設置位置が異なれば，計測情報も異なる．そこで，計測される位置情報の中で，基準となる計測対象(手術機器や患部に設定されたマーカなど)を設定し，任意の手術機器や患者位置とこの基準点との差分として位置情報を取り扱うことで，異なる位置計測装置間で統一的な位置情報の取り扱いを可能とした．光学式位置計測装置 A,B が設置された環境において，基準となる位置を与える機器あるいは患者マーカを X, 計測対象となる手術機器あるいは患者マーカなどを Y とし，P 座標を基準とした Q 座標への座標変換行列を ${}^{Q}_{P}T$ と定義すると，計測対象 X,Y は，計測装置 A からは，${}^{X}_{A}T, {}^{Y}_{A}T$ として，計測装置 B からは ${}^{X}_{B}T, {}^{Y}_{B}T$ として計測される．このとき，基準点 X からの相対位置で表される計測対象 Y の設置位置に依存しない差分位置情報 ${}^{Y}_{X}T$ は，式(1)により共通の情報として取り扱いが可能になる．

$$ {}^{Y}_{X}T = {}^{A}_{X}T \bullet {}^{Y}_{A}T = {}^{B}_{X}T \bullet {}^{Y}_{B}T \qquad (1) $$

3. 評価実験

光学式位置計測装置（POLARIS®, Northern Digital Inc.）と冗長となる小型の光学式位置計測装置(Vicra®, Northern Digital Inc.)を用意した Fig.1 のような統合システムを構築し，臨床での使用を想定した In vivo 環境下において，冗長となる位置計測装置によってオクルージョン問題が発生した場合においても，安定したナビゲーションによる手術支援が実現可能であるか検証を行った．実験では，正常組織にも PpIX が集積したブタ(ランドレース種)の開頭した状況下で，術者が指し示した蛍光発生箇所を光学式位置計測装置から得られる位置情報と対応づけ，ナビゲーション画面上に提示を行った．実験中，光学式位置計測装置がたびたび遮断される場合があったが，オクルージョン発生時には

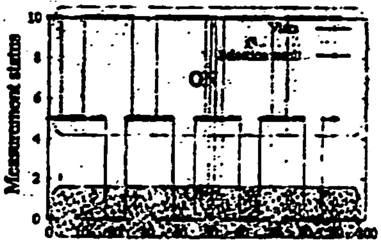

Fig.2 The selection result of optical tracking sensor in case of occlusion

Fig.3 Navigation result in in-vivo experiment

冗長となる位置計測装置が機能し，位置情報に耐障害性のあるシステムが実現されていることが示された(Fig.2)．また，冗長となる位置計測装置を用いたことで，安定したナビゲーションでの手術支援が可能であることが示された(Fig.3)．

4. まとめ

本稿では，光学式位置計測装置のオクルージョン問題に対処し，統一的な位置情報の取り扱いを実現するために，冗長となる光学式位置計測装置を用いた統合システムの開発を行った．臨床を模擬した In vivo 実験により，オクルージョンが発生した場合においても，冗長となる位置計測装置が機能し，ナビゲーションによる安定した手術支援を行うことが可能であった．本研究の一部は，厚生科学研究費補助金「新たな手術用ロボット装置の開発に関する研究」（H15－フィジー002）より援助を受けている．

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06(XIII)-94

5-ALA 誘導 PpIX 蛍光計測による手持ち型局所的脳腫瘍同定システム

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A Handheld Device for Localized Identification of Brain Tumor with 5-ALA Induced PpIX Fluorescence Detection

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Abstract: 5-Aminolevulinic Acid (5-ALA) accumulates on tumors to be metabolized to become ProtoporphyrinIX (PpIX) that is a fluorescent substance. Intra-operative detection of 5-ALA induced PpIX fluorescence provides useful information for tumor detection. We developed a handheld device for localized identification system of brain tumor with 5-ALA induced ProtoporphyrinIX fluorescence detection. The measurement resolution of the device was 0.6mm. This device was designed based on a surgical sucker. The concept was intraoperative detection of residual tumors with a favorite surgical tool and without exchanging the tools. A surgeon tested measurement performance and usability of the device in *in vivo* experiment. Because of the small measurement area of 0.6mm, it was difficult to hold the device during a measurement and to keep the appropriate distance from the target point. It is necessary to add a guide mechanism for positioning, such as using a guide laser beam. And, some other improvements were required about the weight, the size and the grip.

Key words: 5-ALA, ProtoporphyrinIX, Tumor, Neurosurgery, Fluorescence, Handheld Device

1. 背景

脳腫瘍の治療において，特に Glioma などの悪性腫瘍の場合には，腫瘍の摘出率が患者の予後に大きく関わってくる．近年，術前および術中 MRI の情報を基にしたナビゲーションシステムの応用により，大部分の腫瘍を的確に取り除くことはできる．しかし，脳腫瘍は正常組織に浸潤し境界部が不明瞭であるため，境界を肉眼で精確に判断することは難しい．また，MRI によるナビゲーションでは，術中の撮影頻度に限界がある，セグメンテーションやレジストレーション誤差を含む [1]といった理由により，境界部に僅かに残った残存腫瘍を検出するのには不十分である．

脳外科手術では，術者が片手にバイポーラ電気メスを，他方に吸引管を持ち手術を行うことがある．そこで本研究では，吸引管をベースに，残存腫瘍を対象とした 5-Aminolevulinic Acid (5-ALA) 誘導蛍光計測による局所的腫瘍同定システムを搭載した手持ち型のデバイスを開発した．これにより術中の残存腫瘍の検出を従来の持ちなれた器具で行い，また，計測結果に基づき即治療に結びつけることを目的とする．本稿では，製作したプロトタイプと，動物実験において実際に医師に使用してもらった結果を報告する．

2. 方法

2.1. 5-ALA 誘導蛍光による脳腫瘍同定システム

5-ALA は，腫瘍組織に選択的に取り込まれ代謝を経て，蛍光色素である ProtoporphyrinIX (PpIX) に変化する [2]．励起波長のピークは 405nm，蛍光波長のピークは 635nm である [3]．本研究ではφ1mm，波長 405nm のレーザにより局所的に組織を励起し，励起部に近接させた検出光学系（φ8mm）により PpIX 蛍光を取得する．検出光学系のワーキングディスタンスは 16mm±0.5mm であり，空間分解能はφ0.6mm となっている．蛍光は，光ファイバを通して分光光度計でスペクトルを取得し，蛍光のピーク強度とバックグラウンドの強度の比を基に，腫瘍の同定を行う．

2.2. 吸引管への実装

製作したプロトタイプを Fig.1 に示す．土台となる吸

引管は“く”の字型タイプ（フジタ医科器械）を使用した．管先端の下面にPpIX蛍光の検出光学系を，上部に励起用小型レーザモジュールを取り付けた．吸引管先端と検出器による計測領域が干渉しないように，計測点は吸引管先端から5mmの位置とした．

また，計測点の位置座標を取得し，ナビゲーションシステムとの連携を図るため，レーザモジュールの側面および上面に光学式位置計測装置（POLARIS, Northern Digital Inc.）のマーカを取り付けた．

3.　実験

麻酔科で開頭したブタの大脳皮質を対象として，実際に装置を医師に使用してもらい，蛍光計測および操作性の評価を行った．使用したブタは，開頭前に十分な量の5-ALAを投与し，正常組織においてもPpIX蛍光が観察される状態にして実験を行った．

3.1.　蛍光計測の結果と考察

計測した光のスペクトル波形（260nm～900nm）の例をFig.2に示す．検出器の空間分解能が0.6mmと小さいため，空間的な精度の良い計測はできるが，対象の脳表面が計測点から僅かでも外れてしまうと，ほとんど蛍光を検出できなくなってしまうという問題が生じた．

ガイドレーザ等を用いた，何らかのガイド機能を設ける必要がある．

3.2.　操作性の結果と考察

医師からのヒアリングの結果，改良すべき点として挙げられる点を以下に示す．

- 励起用レーザをファイバ導光し，レーザモジュールの分軽量，小型化する
- 通常の吸引管より全体が大きく，重い分，術者が持ちやすいグリップを付ける
- 吸引管としても使用する場合，どうしても先端を曲げたくなるため，吸引管とは独立したデバイスとして作るか，先端がある程度フレキシブルに動くよう改良する

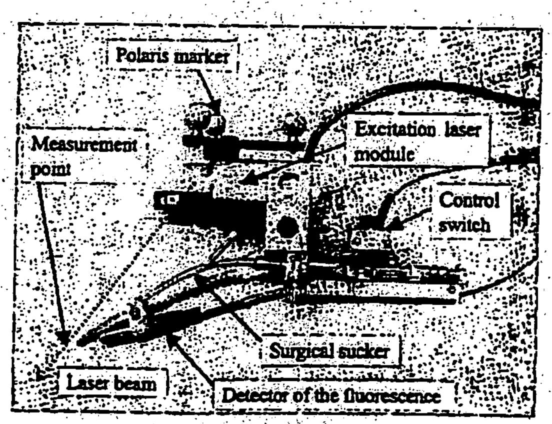

Fig.1　Prototype of the device

4.　結語

吸引管をベースにした，術者手持ち型の5-ALA誘導PpIX蛍光計測による局所的腫瘍同定システムのプロトタイプを製作した．

*In vivo*実験を行い，医師の協力のもと，蛍光計測および操作性の評価を行った．空間分解能が高いため精度が良い反面，僅かな位置合わせのずれで蛍光を検出することができなくなった．そのため，術者へのガイド機能を付ける必要があることが分かった．また今後は，レーザモジュールを省くことによる小型軽量化や，グリップなどのユーザビリティの向上も図っていく．

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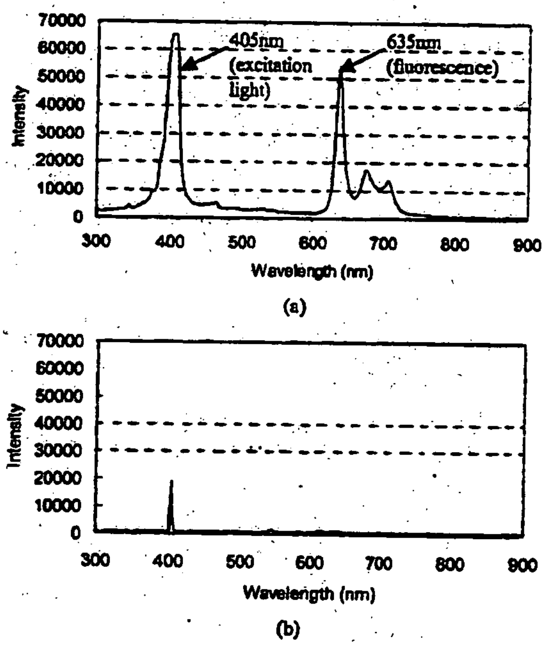

Fig.2　Examples of the measured spectrum. (a) : measurement with appropriate positioning. (b) : measurement with wrong positioning.

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MRI位置姿勢計測法　ー拡張アクティブトラッキングの基礎的評価

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Position and Orientation Measurements Method with MRI –Fundamental Evaluation of Extended Active Tracking

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Abstract: We propose an extended active tracking (EAT) method based on the active tracking algorithm. EAT method is possible to achieve the position and the orientation of the tracking coils synchronically. We use EAT to measure the position of three points by three series of inductance and calculate the orientation of three coils using the measured 3-D positions of coils. In this paper, we conduct three experiments to evaluate the performance of the EAT: 1) background noise reduction with flip angle adjustment, 2) Saturation evaluation of the distance between inductances with various positions and orientations, 3) reproducibility evaluation of the position and the orientation at the same position. The experimental results show that the S/N ratio was 3.90 at 3-degree flip angle, the standard deviation of the distance between inductances was less than 0.67 mm and the standard deviation of the measured position and orientation was less than 0.4 mm and 0.65 degree. These results indicated that our EAT method could be used for position and orientation measurement instead of the conventional tracking method.

Key Words: MRI, Activc Tracking, Navigation System, Minimally Invasive Surgery

1. 背景

内視鏡下手術において，手術ナビゲーションシステムは，非常に有用なシステムである．一方，手術ナビゲーションシステムはリアルタイムに術具の位置姿勢計測が不可欠である．また，手術ロボットを用いて，術具の精密な誘導・制御を行う場合においても術具先端の位置・姿勢を計測する必要がある．本研究では，将来的なMRI下手術を対象とし[1]，MRI下で使用可能かつ体内における術具先端位置を直接計測可能な位置・姿勢計測手法について開発・評価を行ったので報告する．

2. 実験方法・装置

2.1 拡張アクティブトラッキング

アクティブトラッキングは小型受信コイルの三次元位置を計測することが可能な手法である[2]．提案手法である拡張アクティブトラッキングは，トラッキングコイルのインダクタンスを3つに直列分解することで，3点の同時計測を可能としたものであり，3点の三次元位置から小型受信コイルの位置・姿勢を同時に計測することが可能な手法である[3]．

2.2 MRIスキャナ

MRIは試作した実験用0.2Tオープン型MRIを使用した．上下に永久磁石があり，そのギャップは30cmである．0.2Tであることから，水素原子核のLarmor周波数は8.5MHzである．撮像および位置計測にはGE法(TR=40msec, TE=12msec)を使用した．また，計測分解能は0.78mmである(FOV=200mm，周波数方向分解能256点)．

2.3 位置・姿勢計測用受信コイル

開発した位置・姿勢計測用小型受信コイルはインダクタンス成分が3つに直列分解されている．各インダクタンスは中空の樹脂に巻かれており，樹脂内部に信号源として水を封入することで，周辺における水素の有無に関係なく計測が可能である．

3. 評価方法

3.1 水中における信号強度評価

体内における環境，すなわち受信コイル周辺に水素原子核が存在する環境において，各インダクタンスから明確なピークが得られるか確認した．

実験は開発した受信コイルを防水し水中に入れた状態で撮像を行った．フリップアングルを3度，30度，60度