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A Feasibility Study on Image-based Control of Surgical Robot using a 60-GHz Wireless Communication System

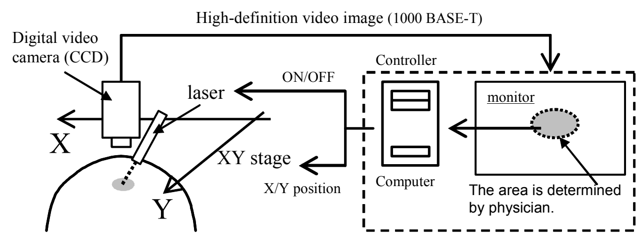
Kenichi Takizawa, Shigeru Omori, Hideo Harada, Ryoichi Nakamura,
Yoshihiro Muragaki, Hiroshi Iseki

***Abstract*—This paper presents an evaluation study on the feasibility of introducing wireless connection into a neurosurgical robot, which is controlled by an image-based navigation system. The wireless connection introduced into the robotic system is based on amplitude shift keying (ASK) at 60 GHz. With this wireless connection, data transmission at the bit-rate of 1 Gbps or more is possible, and here high-definition video images (1080i/1080p) can be transmitted. Such a wireless connection system is implemented in the surgical robot replaces the cable connection between the digital video camera and the controller. In this study, the wireless robotic surgical system is evaluated in terms of its accuracy of navigation using the transmitted video images. The results of a wireless connection test under a line-of-sight (LOS) environment show that navigation accuracy observed when using this wireless surgical robot is comparable to that when using a wired robotic system.**

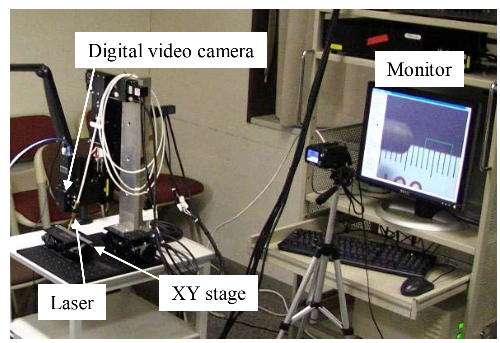
I. Introduction

ROBOTIC surgery has been identified as a useful tool for performing minimally invasive surgery since it allows precise control of manipulators by monitoring video or MRI images [1]. An example of such a surgical robot is da Vinci; using this robot surgeon can control the manipulators via a monitoring endoscope [2]. Recently, advanced surgical robots that utilize an image-based navigation system for precise control of the manipulators have been developed [3]. Such navigation systems are expected to help mitigate the risk involved in a surgical procedure and reduce the work load of the surgeon and the medical staffs.

Nevertheless, the development and applicability of these surgical robots is restricted because they have wired connections. In currently available surgical robots, the manipulators, video camera or MRI system (used to obtain image information), monitor display, and computer (which controls the entire robotic system) are connected by cables. However, in the near future, surgical robots will be expected to collect a large amount of precise information on the patient's condition through vital sensors; hence the cables used in the robotic system would occupy a large area of the floor of the operating room. This would restrict the movement of the robot and the surgeon in the operating room. Hence, the use of a wireless surgical robotic system is preferred. However, the reliability on the connection of using a wireless communication system in medical applications remains to be confirmed.



(a) Overview of the surgical robot used for neurosurgery



(b) Photograph of the system

Fig. 1. Illustration of the surgical robotic system used for neurosurgery. Image recorded by the digital video camera is used to define the area irradiated by the laser. The laser is controlled by a computer that calculates the ON/OFF and XY position from the defined area.

In this study, we develop a surgical robot with a wireless communication system for performing neurosurgeries. The wireless system uses a 60-GHz frequency band, in which there is minimum interference form other wireless network systems installed in hospitals. This wireless connection eliminates the use of a cable between the high-definition digital video camera and the controller. This neurosurgery system employs an image-based navigation system to control an XY stage and laser. In this case, serious errors caused during the transmission of the video image may decrease the accuracy of the laser irradiation; these errors result from the errors in the position of the XY stage and the time taken to switch the laser ON/OFF.

The wireless robotic surgical system is evaluated on the basis of its ability to suppress the abovementioned errors by using wireless connections. The rest of this paper is organized as follows. In the following section, details of the wireless

K. Takizawa is with the National Institute of Information and Communication Technology (NICT), 3-4 Hikarino-oka, Yokosuka 239-0847, Japan. (e-mail: takizawa@nict.go.jp).
S. Omori and H. Harada are with TERUMO Corporation, 1500 Inokuchi, Nakai-machi, Ashigarakami-gun, Kanagawa 259-0151, Japan..
R. Nakamura, Y. Muragaki, and H. Iseki are with the Faculty of advanced techno-surgery, Institute of advanced biomedical engineering and science, Tokyo Women's Medical University, Tokyo, Japan.

robotic surgical system are illustrated. Section III included the results of the test controlled to evaluate the system. Section IV includes concluding remarks.

II. ROBOTIC SURGERY USING 60-GHZ-BAND WIRELESS COMMUNICATION SYSTEM

A. Overview of the robotic surgical system

The robotic surgical system used in this experiment has been developed for performing neurosurgeries [4]. A block diagram of this system is shown in Fig. 1. With this system, malignant tumor in the brain can be removed using a 150-µm laser; the process is carried out by using a computer navigation system that allows real-time video images of the surgical area to be captured. In this system, the controller decides the position and turn ON/OFF of the laser through image-based navigation. The video image (1080p/1080i) is recorded by high-definition video camera. The frame rate is set to 60 frame/s. In the surgical system using wired connection, the video camera is connected to the controller by an Ethernet cable, and the video image is transmitted through a 1000 BASE-T cable using UDP/IP. The control commands generated by the controller are transmitted to the laser and XY stage via a parallel communication interface (PCI) bus or a serial bus (e.g., RS-232C).

The XY stage moves with a velocity of 4 mm/s along the X- and Y-axes. In this surgical system, a permissible error of the laser irradiation is 0.5 mm. In this case, the acceptable delay time is 125 ms or lesser; this value is obtained by dividing the permissible error by the velocity of the XY stage. In other words, the difference between the time at which an image is recorded by the video camera and that taken to start the laser irradiation must be 125 ms or lesser. This makes video compression difficult because a considerable delay time is introduced when a compression technique that uses the correlation between successive video frames is used.

In this study, we introduce a wireless connection in our robotic surgical system for elimination of the difficulties caused by the use of cables. The system using wireless connections is expected to be highly flexible and is possible to make the surgical process easy for the surgeon and medical staffs. However, the development of such a wireless system is a challenging task.

The wireless connection to be implemented in the robotic surgical system must satisfy the following requirements:

1) It should be unaffected by other wireless systems in the hospital.
2) It should have a sufficiently high data transmission rate so that high-definition video images are transmitted with out compression and problems due to delay time are avoided.

Wireless local area networks (WLANs) such as 802.11g or the draft version of 802.11n are popular wireless connections used for wireless video transmission; however, the use of 2.4- and 5-GHz frequency bands remains concerns on RF interference because these frequency bands are commonly used in hospitals. In addition, the data transmission rate achieved with a WLAN is not sufficient for the transfer of uncompressed high-definition video images since the maximum throughput of a 11g WLAN is only 30 Mbps, while that of the draft version of 11n is 150 Mbps. Thus, we need to find another wireless communication system which provides sufficient data transmission rate without harmful RF interference between other radio systems.

TABLE I
AVAILABLE FREQUENCY BAND IN DIFFEREMET COUNTRIES [5]

Country	Frequency band
USA	57.0 – 64.0 GHz
EU	57.0 – 66.0 GHz
Canada	57.0 – 64.0 GHz
Japan	59.0 – 66.0 GHz
Australia	59.4 – 62.9 GHz
Korea	57.0 – 64.0 GHz

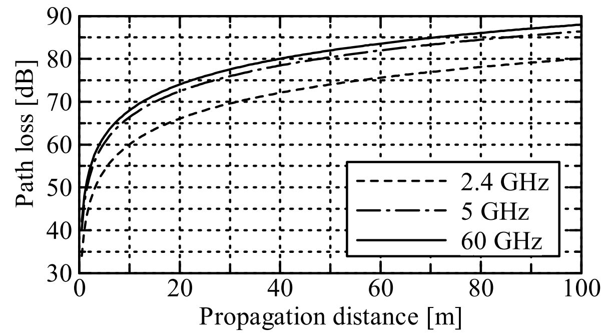


Fig. 2. Path loss in free space at 2.4, 5, and 60 GHz. Note that 20-dB antenna gain is included in the path loss at 60 GHz.

B. 60-GHz wireless connection

We focus on the use of 60-GHz wireless connection, which has gained popularity since standards using this frequency band are employed in wireless high-definition video transmission interfaces such as High Definition Multimedia Interface (HDMI) [6, 7]. These wireless standards enable high-speed data transmission at the rate of 1 Gbps or more. As shown in Table 1, unlicensed wireless systems operating in the 60-GHz band are being used in many countries.

During transmission, 60-GHz RF signals are attenuated to a greater extent than that of 2.4- or 5-GHz RF signals. Fig. 2 shows the attenuation in free space at 2.4, 5, and 60 GHz. In the path loss at 60 GHz, please note that 20-dB antenna gain is included. The attenuation of the RF signals, known as path loss, in free space is given by the Friss's equation as

$$L(f,d) = 20 \log_{10}\left(\frac{1}{4\pi d}\cdot\frac{c}{f}\right) \quad \text{[dB]}, \qquad (1)$$

where c is the speed of light, d is the distance between the transmitter and the receiver, and f the frequency of the RF signals. If the permissible transmission power and receiver sensitivity are assumed to be 10 dBm and -70 dBm, respectively, the possible path loss is 80 dB. The results shown in Fig. 2 demonstrate that the 60-GHz wireless connections can be used when d is 40 m or lesser. The

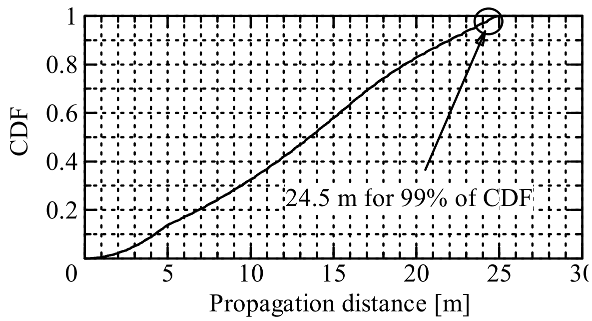


Fig. 3. CDF of the propagation distance between transmitter and receiver in a room in size of 10m x10m.

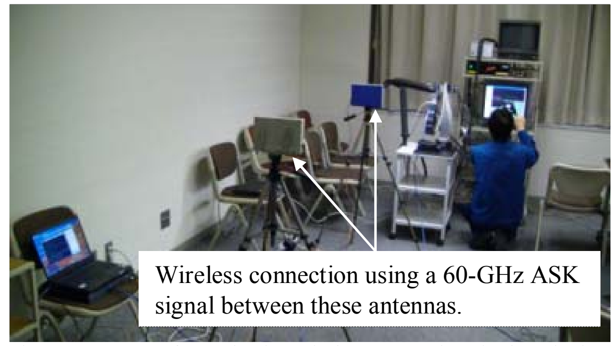


Fig. 4. Test setup for evaluating wireless connections in the robotic surgical system using a 60-GHz ASK signal.

transmission range required to control the proposed surgical robotic in the operating room is typically 10–20 m. Fig. 3 shows the cumulative distribution function (CDF) on the light distance in a 10 m × 10 m operating room when up to third reflections at the walls are considered. This CDF on the distance is obtained by the general ray-tracing approach. It is confirmed that the propagation distance in such an operating room is typically 10–20 m and that 99 % CDF is achieved at a propagation distance of 24.5 m. The acceptable propagation distance derived from the result shown in Fig. 2 is 40 m. Therefore, it is confirmed that 60-GHz wireless connections are suitable for the proposed wireless robotic surgery system.

TABLE II
SPECIFICATIONS OF THE BB.LINK

Carrier frequency	60 GHz/63 GHz
Transmission power	10 mW
Transmission range	25 m*
Data rate	1.25 Gbps
Media access control (MAC) method	Full duplex
Modulation	ASK
Interface	1000 BASE-SX

*: The transmission range depends on the surrounding environment.

C. *Wireless robotic surgical system using 60-GHz wireless connection*

In the wireless surgical robotic system, cable connections between the digital video camera and the controller (Fig. 1), are replaced by 60-GHz wireless connections. BB.LiNK designed by NEC Engineering Corp. [8] is used as the wireless connection.

The specifications of the wireless system are summarized in Table II. With BB.LiNK, full-duplex data transmission is possible with amplitude shift keying (ASK) modulation. Full-duplex data transmission in the frequency domain helps minimize time delays when the transceiver switches between the transmit and receive modes. This is important for systems that are sensitive to time delay. BB.LiNK uses a 1000 BASE-SX interface even though the digital video camera and controller use a 1000 BASE-T interface. Hence, an interface converter is introduced between 1000 BASE-T and 1000 BASE-SX. The delay time caused by the use of the abovementioned converter in the robotic system is less than 1 ms, as measured by "ping" command. The beam width of the deployed antenna is 13°and the gain is around 10 dBi. The transmission power is 10 mW, which satisfies the criteria for the use of 60-GHz systems in Japan. Since the maximum transmission power is 100 mW in US and Europe, the coverage area can be expanded by simply boosting the transmission power.

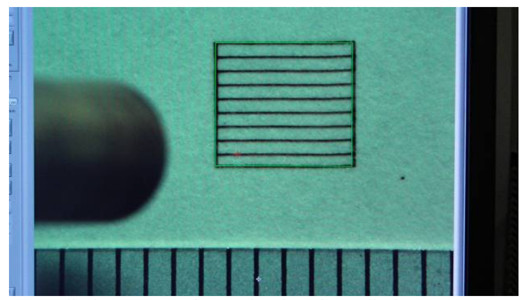


Fig. 5. Radiation pattern for evaluating the radiation error caused by introducing a wireless connections into robotic surgery system (left: the tip of the laser, bottom: the scale indicates 1 mm).

III. PERFORMANCE EVALUATION

A. *Test setup*

We experimentally evaluate the wireless surgical robotic system from the viewpoint of accuracy of the laser irradiation. The setup for this test is shown in Fig. 4. A test laser radiation pattern is traced on a sheet of paper, as shown in Fig. 5. Then, the difference between the requested and resulted pattern is measured on the video image. This test is conducted in an office room. The nearest wall is located at a distance of 90 cm from the line-of-sight (LOS) path. *d* is increased from 1.5 m to 4.5 m in 1.5-m steps.

B. *Test results and discussion*

The results obtained in this test are summarized in Table III. Results obtained when cable connections are used are also included in this table for comparison. The accuracy of laser irradiation is less than 0.05 mm under all measurement conditions. These results satisfy the permissible error (0.5 mm) shown in II.A. Under the given experimental conditions, the accuracy of the wireless system is comparable to that of the wired system.

Table III also shows the measured specifications of the wireless connection from the viewpoint of networking. The measured throughput is maintained at a value greater than 900

TABLE III

TEST RESULTS ON THE WIRELESS CONTROL USING THE SURGICAL ROBOTIC SYSTEM

Connection conditions	Error in laser irradiation	Throughput	RTT*	Jitter
wireless (d = 1.5 m)	0.04 mm	910 Mbps	< 1ms	0.41 ms
wireless (d = 3.0 m)	0.06 mm	908 Mbps	< 1ms	0.40 ms
wireless (d = 4.5 m)	0.04 mm	906 Mbps	< 1ms	0.51 ms
wired	0.04 mm	913 Mbps	< 1ms	0.49 ms

*RTT: Round-trip time

Mbps, which is sufficient for transmission of the high-definition video images from the digital video camera. Since the throughput is maintained in more than 900 Mbps during the test, the measured round-trip time (RTT) between the digital camera and the controller is less than 1 ms. This RTT is the delay time caused by the additional part to introduce the wireless connections into the surgery system. From the measured RTT, it is apparent that the time delay caused by the use of the wireless connection is considerably lesser than the acceptable value for surgical system (125 ms). The introduced wireless connection provides jitter in the packet arrival timing of less than 0.5 ms, which is in the acceptable range, because the measured jitter does not affect the frame duration of the video image (given by 1/60 = 16.7 ms).

The obtained results show that the 60-GHz wireless connection can be successfully used in place of cables between the digital video camera and the system controller. However, the test conducted in the office room is only preliminary. In our future study, we plan to carry out performance evaluation test in an operating room.

IV. CONCLUSION

In this study, we used a surgical robotic system in which a 60-GHz wireless system using ASK and full-duplex data transmission was implemented. The test results of the tests performed on this system demonstrated that the error in laser irradiation was comparable to that in a wired system; this was because the high throughput obtained with the 60-GHz wireless connections facilitated the transmission of high-definition video images under the given test conditions.

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