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Autonomous Avoidance based on Motion Delay of Master-Slave Surgical Robot

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***Abstract*— Safe use of master-slave robots for endoscopic surgery requires autonomous motions to avert contact with vital organs, blood vessels, and nerves. Here we describe an avoidance control algorithm with delay compensation that takes the dynamic characteristics of the robot into account. To determine the operating parameters, we measured frequency characteristics of each joint of the slave-manipulator. The results suggest this delay compensation program improves avoidance performance.**

I. Introduction

Research suggests master-slave robots will find increasing use in endoscopic surgery [1], [2]. Accurate and precise manipulations are now possible, but locating and steering clear of vital organs, vessels, and nerves remain unsolved problems. Tissue boundaries are often obscure, and information on depth is lacking. Consequently, there are serious risks of unintended contact and injury. Navigation technology with a diagnostic imaging system makes it possible to obtain positional information [3]-[5]. So, adding an avoidance algorithm to such a system might improve the safety of endoscopic master-slave robots.

Figure1 shows an overview of the system. The flow of operation is as follows: 1) Take 3D positional information of critical areas using MRI; 2) Decide the avoidance motion of the slave-manipulator based on this information; 3) Communicate the slave motion to the operator.

Industrial and mobile robots have well developed systems for autonomous avoidance [6]-[10]. Application of similar systems to complex environments encountered by surgical robots is a worthy but distant goal. There are two major problems:

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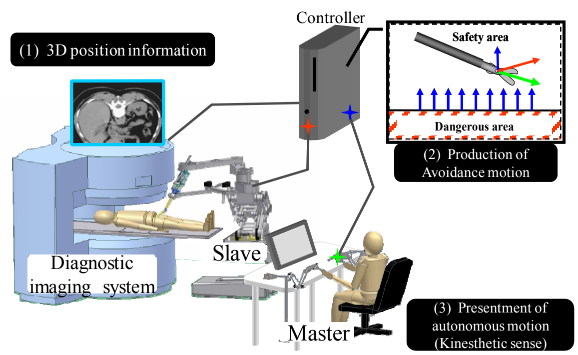


Fig. 1 Autonomous avoidance system

1) Tissue Movements: Vital structures move when the patient breathes or when surgical instruments distort the local environment.

2) Delay in Robot Motion: To operate using non-invasive positional information, robots work within the MRI system shown in Fig. 1. Signal transmission from a remote location controls robot motion through actuators located outside the MRI gantry, which has a strong magnetic field. An unavoidable time delay associated with the transmission poses a problem for autonomous avoidance.

II. Generation of Autonomous Avoidance Motion

Autonomous avoidance requires precise, stable movements of surgical instruments. Khatib and colleagues developed an induction strategy for robots based on the concept of a potential field [6], [7]. Attractions to the target and repulsion from obstacles were realized at the same time. Repulsion increased as the manipulator approached hazardous areas. Fluctuating hand movements of the operator interfered with the trajectory, however. Stability was difficult to achieve. Jakopec et al. proposed a method to decelerate the robot at an arbitrary distance from a vital structure [10]. Nevertheless, when the structure moved toward the robot, the avoidance mechanism was not active.

We derived an equation that combines the solutions of both problems to achieve stable movement:

$$k_s \dot{x}_{SlaveN} = k_m \dot{x}_{MasterN}(1 - \frac{k_r}{d^n}) - \frac{k_r \alpha}{d^n} \quad (1)$$

$\dot{x}_{SlaveN}$ is the velocity of the slave-manipulator, $\dot{x}_{MasterN}$ is the velocity of the master-manipulator, and d is the distance from the structure to be avoided. k_s, k_m, k_r, n , α are constants.

The first term on the right side of equation (1) indicates the decelerating input from the master-manipulator. Manipulator velocity becomes 0[m/s] at distance d_o in equation (2):

$$d_o = k_r^{\frac{1}{n}} \quad (2)$$

The second term on the right side of equation (1) shows that repulsion increases as the manipulator approaches areas with potential hazards. Vital structures that move toward the slave-manipulator generate repulsion to avoid them.

III. Delay Compensation Algorithm

Fig. 2 is a block diagram of the method. “Avoidance control” stands for (1). For precise avoidance, two issues are key:

1) Measurement of position in real-time. In general, an internal sensor such as an encoder of the motor estimates the position of the slave-manipulator. The registration between the sensor and information on the position of target structures involves a certain level of error, however. So, the external sensor should measure the position of the slave-manipulator as well as the position of the structure.

2) Prediction of slave position. A time delay in signal transmission reflects differences between target movement and robot movement. Therefore, predictions of position should take such time delays in to account.

We propose a control algorithm that includes both real-time information and prediction of slave position (Fig. 3). Equation (3) uses operating characteristics to predict slave position:

$$x_{sp} = x_{sR} + x_s - x_{sM} \quad (3)$$

x_{sp} is the predicted position, x_{sR} is the target position, and x_{sM} is the modeled position. An external sensor measures position x_s.

Predicted position x_{sp}, determines slave motion without using measured position x_s directly. This algorithm resolves both the time delay and the registration error.

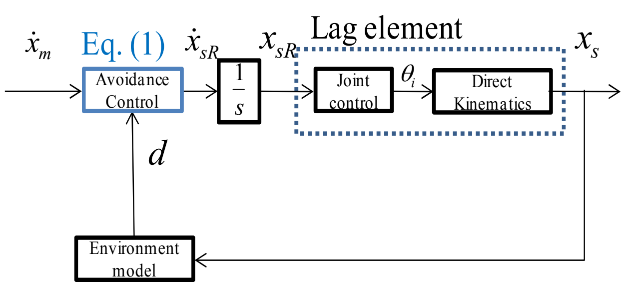


Fig. 2 Block diagram (without delay compensation)

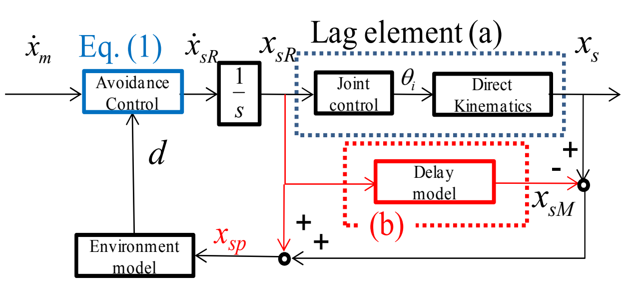


Fig. 3 Block diagram (with delay compensation)

IV. Modeling of Slave-Manipulator

Fig. 4 depicts our slave-manipulator [11]. It has six degrees of freedom and consists of a *positioning-manipulator* and a *forceps-manipulator*. The positioning-manipulator is a selective compliance assembly robot arm (SCARA) with two degrees of freedom. The design of manipulator will allow it to operate within the MRI gantry, and a remotely controlled timing belt moves each joint. The forceps-manipulator has a prismatic joint with degree of freedom for positioning. There are also differences in actuator type and drive transmission that affect the operating characteristics. Accordingly, we measured the amplitude and phase frequency response of each joint to develop both manipulators.

1) Method: We used 3D motion capture OPTOTRAK® to measure frequency responses of each joint. Then we made Bode diagrams to compare the input and response.

2) Results and modeling: Figs. 5 and 6 graph example measurement values and estimated model for the positioning-manipulator. Equation (4) is the transfer function of the model. w_n is the resonance angular frequency, ζ is attenuation coefficient, and L is the delay time. Table 1 lists the parameters of the each joint.

$$G_M(s) = \frac{w_n^2 e^{-sL}}{s^2 + 2\varsigma w_n s + w_n^2} \quad (4)$$

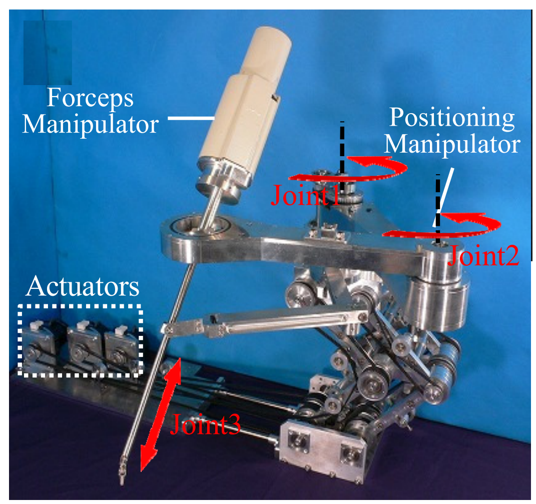


Fig. 4 Slave manipulator

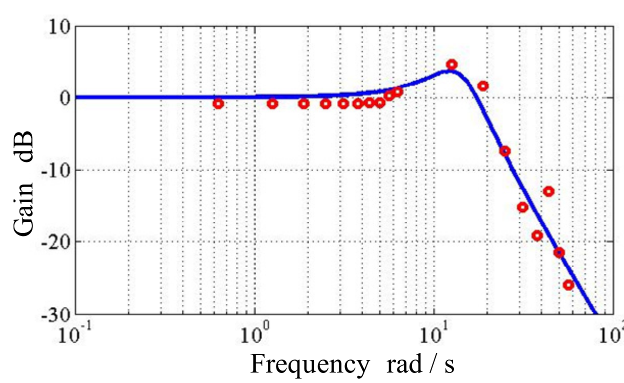


Fig. 5 Frequency response (Amplitude)

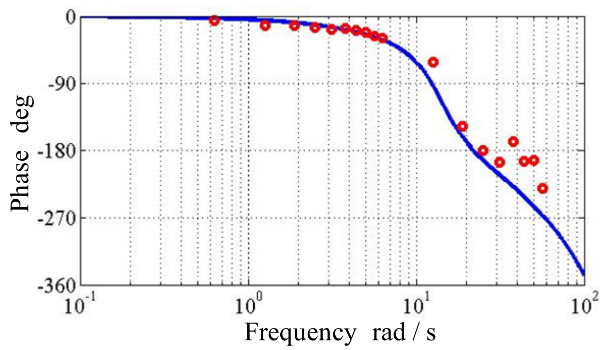


Fig. 6 Frequency response (Phase)

Table 1 Modeling parameters

	Positioning		Forceps
	Joint1	Joint2	Joint3
w_n	14.1	9.4	23.9
ζ	0.35	0.45	0.35
L	0.03	0.0	0.0

V. Experimental Evaluation

A. Experimental Method

Two configurations represent the area to be avoided: the X-Z plane and the Y-Z plane. Figs. 7 and 8 depict the experimental environment with the area set in the X-Z plane. Each parameter in equation (1) is at a distance d_o of 2.5 [mm], and the slave manipulator approaches at constant velocity.

Under these conditions, we compared the avoidance motion of the slave-manipulator with and without delay compensation. 3D motion capture OPTOTRAK® measured the position of the area and tip.

B. Experimental Results

Figs. 9 and 10 plot the experimental results. The vertical axis marks the distance between the setup area and tip of the slave-manipulator, and the horizontal axis is the time.

Fig. 9 (a) is a graph of the situation when the manipulator broke into the hazardous area. This result suggested that the avoidance required delay compensation. Fig. 9 (b) indicated that the manipulator avoided the area with compensation at distance d_o. In Fig. 10, overshoot to distance d_o decreased with delay compensation.

C. Discussion

Delay compensation improved avoidance performance in both the Y-Z plane and the X-Z plane. The findings suggest delay compensation by signal transmission resolves differences in operating characteristics. Nevertheless, overshoot depends on the direction of motion. It was 1.7 [mm] toward the Y-Z plane and 1.0 [mm] toward the X-Z plane. Overshoot may result from modeling error. If so, the error of the positioning-manipulator exceeds that of the forceps-manipulator and requires a correction. The positioning manipulator moves mainly in the X-Z plane, while the forceps manipulator moves mainly along the Y axis. Further studies may help us better understand autonomous avoidance with stable movements in this robot.

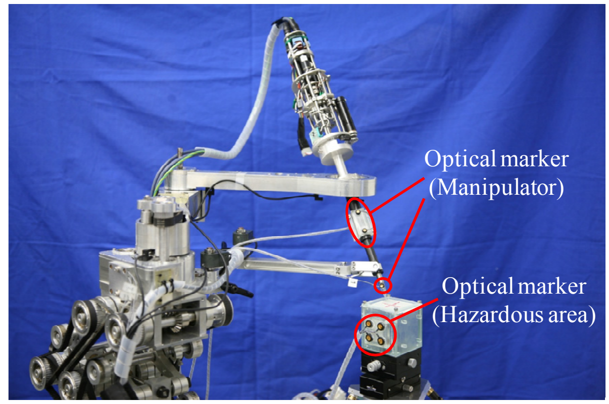


Fig. 7 Overview of experimental environment

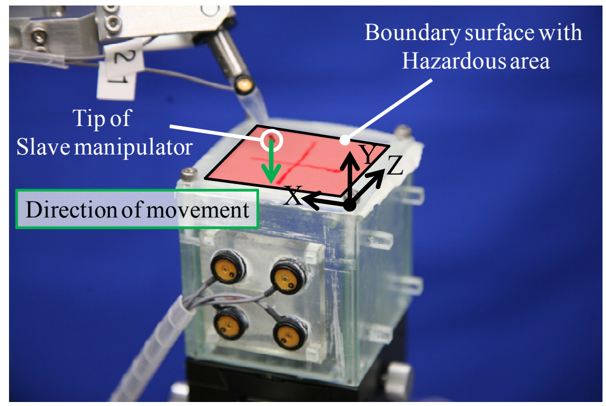
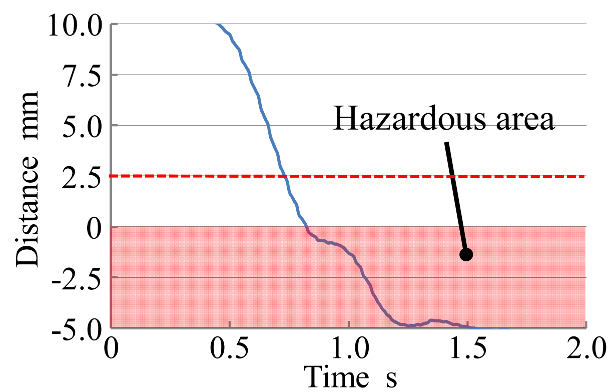
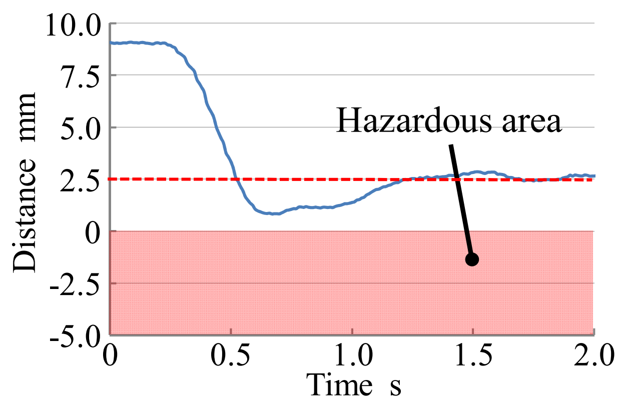


Fig. 8 Coordinate axis of experimental environment

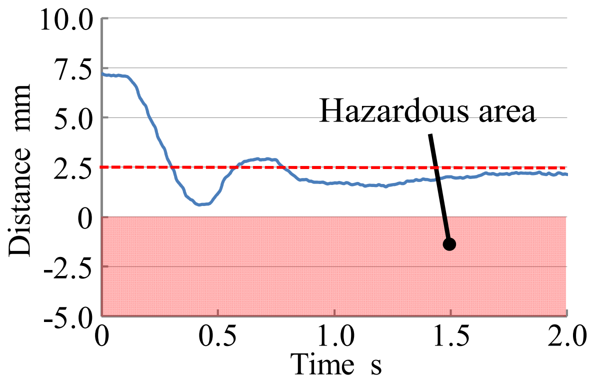


(a) Without delay compensation

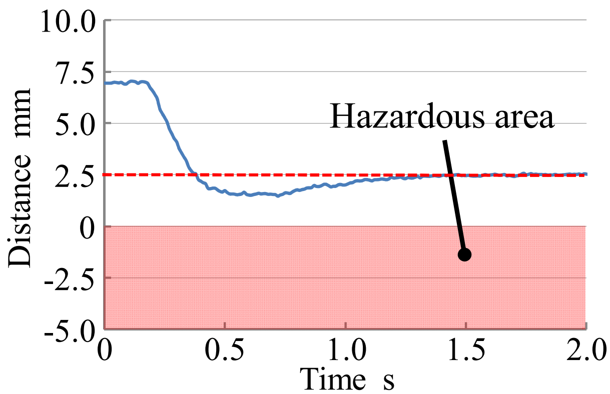


(b) With delay compensation

Fig. 9 Experimental results (Y-Z plane)



(a) Without delay compensation



(b) With delay compensation

Fig. 10 Experimental results (X-Z plane)

VI. Conclusion and Future Work

Here we present a master-slave robot with avoidance control that includes a delay compensation algorithm. The algorithm predicts position of the slave-manipulator and resolves the problem of motion delay. We measured frequency characteristics of each joint to determine the operating characteristics of the robot. Our findings suggest the algorithm improves autonomous avoidance. Future work will focus on accuracy of the model and stability of motion.

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