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DETECTION OF ROBOTIC FORCEPS CONTACT WITH AN ORGAN USING FORCED SHAFT OSCILLATION

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Abstract. *Surgical robots are used in hospitals all over the world. However, some accidents have occurred in which contact by the robotic forceps shaft has injured an organ. To prevent such accidents, detection of contact between the shaft and an organ is needed but attaching pressure sensors or strain gages increases the shaft diameter. Therefore, we proposed a method that could detect shaft contact with an organ indirectly using a piezoelectric oscillator and two accelerometers which were attached to the shaft. Bode magnitude plots of the transfer functions between the two accelerometers showed that the gain magnitude decreased when the contact force on the shaft increased from 0 N (no contact) to 10 N (emergency contact).*
Keywords: Robotic surgery, Teleoperation, Oscillation mode analysis

1. **Introduction.** Commercial robotic surgery systems have been used since the late 1990s. Robotic surgery can generally contribute to minimal invasiveness and safety [1]. The most well-known surgery robot, the *da Vinci* surgical system (Intuitive Surgical, Inc., USA), is a master-follower type teleoperation system [2]. This robotic forceps, which has more than four degrees of freedom, moves within the intraperitoneal space of the patient under a surgeon's control. However, the current commercial models of *da Vinci* and other surgical robots do not provide a force feedback function. Therefore, surgeons need to confirm contact between the tissues and forceps by stereoscopic vision and careful operation of the robot. There are many studies that develop a force feedback system by attaching force sensors to the grasper of the robotic forceps. The results of these studies show that force feedback by visual, audio, and haptic methods can improve the safety and controllability of robotic surgery systems [3-7].

On the other hand, there have been accidents that occurred in robotic surgeries due to contact from the forceps shaft. However, contact between the forceps shaft and organs is not reflected in an endoscope view [8], and force feedback systems cannot detect such contact. To detect the contact directly, pressure sensors or strain gages can be used but this inevitably increases the diameter of the shaft. Therefore, the invasiveness of the surgery is increased if direct measurement methods are applied.

In this study, we proposed an indirect method that detects the contact force on the shaft of the robotic forceps. One oscillator and two accelerometers were attached in parallel on the shaft near the gearbox. The oscillator was used for the forced oscillation, and the transfer function between the two accelerometers was obtained.

In this research, we reported the changes in the transfer functions of the magnitude plots between the two accelerometers when the contact force on a pseudo-organ was changed. We statistically evaluated when the contact force changed and selected the specific frequency, which was used for detecting the contact force. Using the specific frequency, we developed a prototype of a contact detection system, which discriminates the shaft contact states into three patterns in real time: safety, warning, and emergency.

2. Methods.

2.1. Shaft contact detection system. An accident involving the rupture of the pancreas was caused by a shaft contacting. This study aims to prevent such an accident by proposing a detection system for the contact between a robotic forceps and an organ. Figure 1 shows the configuration of the proposed system. The forceps is detachable from the robotic arm of the main body of the robot and comprises three parts: gearbox, shaft, and grasper. An oscillator and two accelerometers are attached to the shaft near the gearbox in order not to disturb the surgery. Accelerations are recorded when the oscillator oscillates the shaft and the transfer function between the accelerometers is estimated. The continuously estimated transfer function is used to detect the contact of the shaft with the organ.

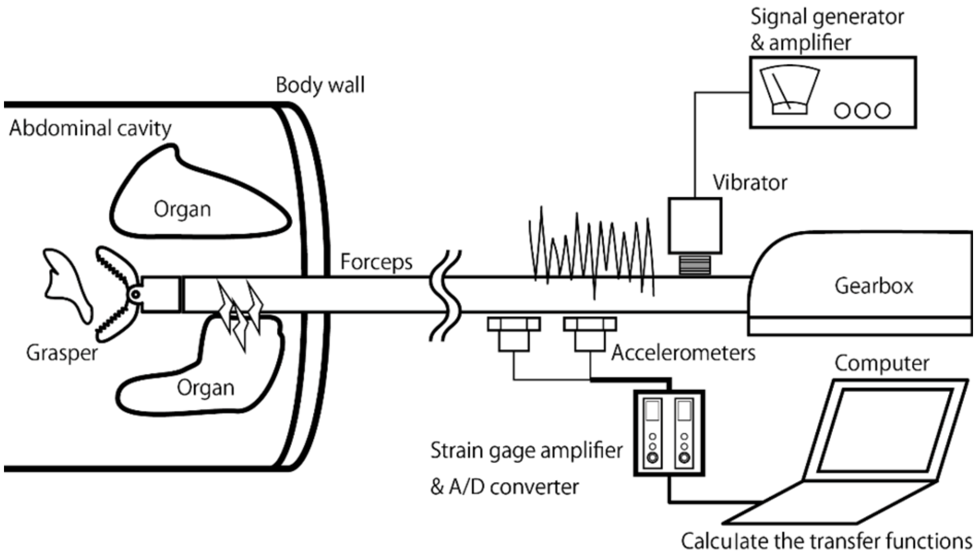


FIGURE 1. Configuration of the proposed contact detection system

2.2. Oscillator for the forced oscillation of the forceps. We used layered piezoelectric ceramics (PAC133C, NTK CERATEC Co., Ltd.) as the oscillator for the forced oscillation of the forceps shaft. The piezoelectric ceramic had a 1.5-μm displacement and wide frequency specifications. The actuator was sandwiched between an aluminum contact part and a weight, which was a bolt and nut, and was attached to the shaft by a holding clip which was made using a 3D printer (see Figure 2). The maximum length sequence (MLS) (cycles: $2^{32} - 1$, sampling rate: 10 kHz) was input to the piezoelectric actuator using an audio amplifier (A100a, Yamaha Co.). An MLS is a signal that contains pseudo-binary signals and is frequently used for system identification.

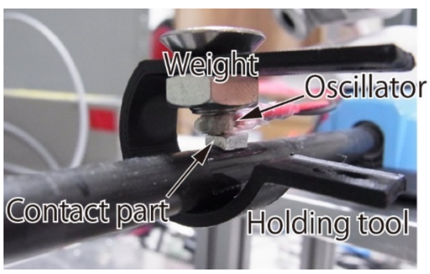


FIGURE 2. Oscillator for the forced rotation

2.3. **Accelerometers for obtaining the transfer functions.** Accelerometers (NP-2910, Ono Sokki Co., Ltd.), which were attached to the shaft by a holding tool as shown in Figure 3, measured the accelerations at specific points on the shaft. These signals were recorded on the PC at a 20 kHz sampling rate using a charge amplifier (CH-1200, Ono Sokki Co., Ltd.).

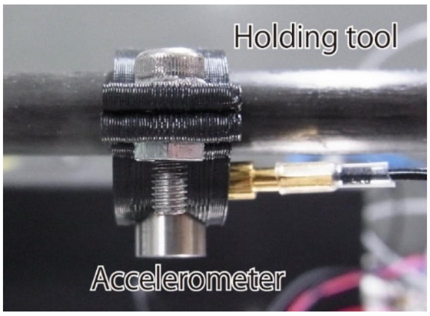


FIGURE 3. Sensor for recoding the acceleration at a point on the shaft

2.4. **Obtaining the transfer functions.** The robotic forceps were fixed to the robot arm; the shaft of the forceps was assumed to be a cantilever at a forced oscillation. The x-axis extended in the gripper direction of the shaft. Here the displacements in the vertical direction at the locations of the accelerometers were set as $y_A(x,t)$ and $y_B(x,t)$. The relationship between these terms can be written as

$$y_B(t) = \int_{-\infty}^{\infty} h(t) \cdot y_A(t-\tau) d\tau.$$

This relationship can be transformed to the frequency domain:

$$Y_B(\omega) = H(\omega) \cdot Y_A(\omega),$$

where $h(t)$ and $H(\omega)$ are called as transfer functions.

The frequency domain representation $Y_A(\omega)$, $Y_B(\omega)$ can be obtained from the frequency representation of the measured accelerations $\ddot{Y}_A(\omega)$, $\ddot{Y}_B(\omega)$:

$$Y_A(\omega) = -\frac{1}{\omega^2}\ddot{Y}_A(\omega),$$

$$Y_B(\omega) = -\frac{1}{\omega^2}\ddot{Y}_B(\omega),$$

and the transfer function can be obtained from the following equation:

$$H(\omega) = \frac{Y_B(\omega)}{Y_A(\omega)} = \frac{\ddot{Y}_B(\omega)}{\ddot{Y}_A(\omega)}. \tag{1}$$

3. **Experiment.**

3.1. **Experimental setup.** In this study, we examined the oscillation modes when the contact force on a pseudo-organ was changed. As shown in Figure 4, the oscillator position was set at $x = 7$ cm and the accelerometers were set at points A ($x = 15$ cm) and B ($x = 21$ cm). The slider stage was attached in a vertical orientation and the sponge pseudo-organ was set on the stage. This organ was pressed in an area 3 to 6 cm from the end of the forceps ($x = 36.2$ to 39.2 cm), which was within the dead angle of the endoscope cameras. We measured the contact force on the pseudo-organ using a load cell which was located under the floor of the stage.

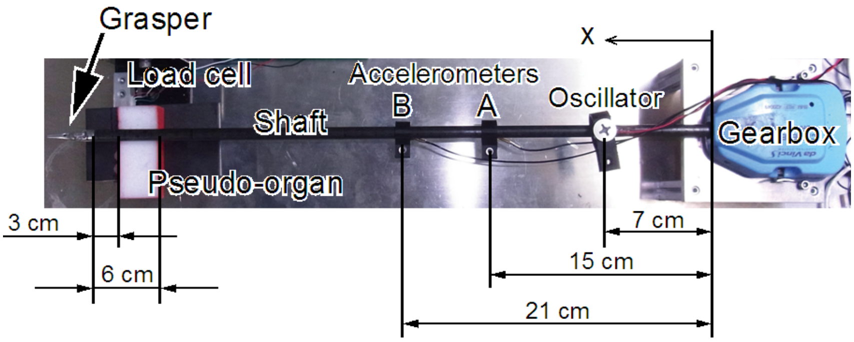


Figure 4. Experimental setup for obtaining the transfer functions between points A and B when the contact force was changed

3.2. **Specific frequency selection for detecting contact with the organ.** We obtained the transfer functions while the contact force of the shaft on the organ was changed from 0 N (no contact) to 10 N, in 2-N increments. The compression yield stress of the pig's liver was at least over 130 kPa [9]. We assumed that the compression yield stress of pancreas of the human was also 130 kPa. In this experiment, the contact area of the pseudo-organ was 255 mm^2 (8.5 mm $\times$ 30 mm). At a pressure of 130 kPa, the contact force to the pseudo-organ was 33 N. Thus, for the safety threshold, the limitation of the contact force was set to 10 N, whereas that for the alert threshold was set to 2 N.

The transfer functions were obtained from each 250 ms of data. The power spectrum densities of the measured acceleration, which assumed that the system was a 50-order autoregressive model, were obtained by the maximum entropy (Burg) method [10] and the transfer functions were obtained from (1). The average magnitudes at each frequency, when the contact forces were 0, 4, and 10 N, are illustrated in Figure 5. In this figure, the shapes of the magnitude plot are similar even when the contact forces are different. In this study, we employed a 2.45-2.75 kHz frequency band to detect the contact of the shaft on the organ.

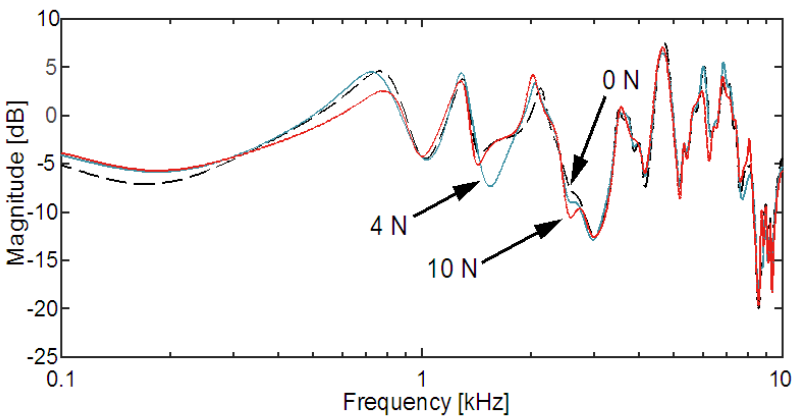


Figure 5. Magnitude plots of the force on the pseudo-organ being 0, 4, and 10 N

3.3. **Statistical evaluation.** Figure 6 shows the distributions of the measurement plots of the average magnitudes in the 2.45-2.75 kHz band when the contact force on the shaft was changed. This figure shows that the average magnitude tends to decrease as the contact force increases. The results of Welch's t-test showed that there were significant differences between the averages of any combinations from 2 to 10 N. The p-value was 8.01×10^{-6} between the average magnitudes from 0 to 2 N which was a significant difference. From these results, the developed system could detect shaft contact with the organ if the contact force was more than 2 N.

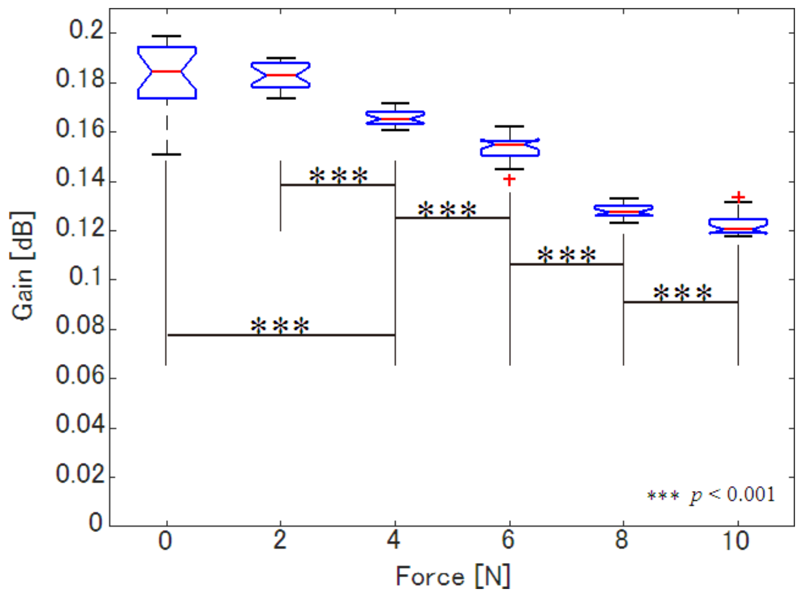
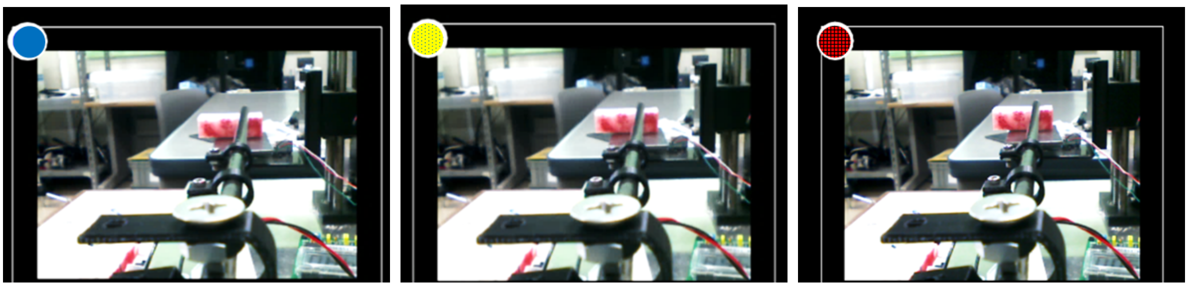


Figure 6. Relationships between the magnitudes of the 2.45-2.75 kHz band and the contact forces

4. **Development of the Prototype System.** We developed a prototype system that could detect shaft contact with an organ using the change of the average magnitude in the 2.45-2.75 kHz band. To reduce the calculation cost, we estimated the power spectrum density in real time (every 250 ms) by discrete Fourier transform instead of the maximum entropy method. This system discriminated the estimated contact force into three patterns and set two thresholds Th_1, Th_2 ($Th_1 < Th_2$). When the average magnitude in the 2.45-2.75 kHz band $G(t) < Th_1$, the contact force was less than 2 N (safe). When $Th_1 \leq G(t) < Th_2$, the contact force was assumed to be 2-6 N (caution) and when $G(t) > Th_2$, it was assumed to be more than 8 N (emergency). In this study, the two thresholds were defined as $Th_1 = 0.170$ dB and $Th_2 = 0.135$ dB.

Figure 7 shows examples of the operation view of the prototype system. The camera view does not reflect the contact between the shaft and organ during the operation at actual situation. However, this prototype system showed contact between the organ and shaft in a demonstration. The color of the circle at the top-left corner of each operation view represents the discriminated contact state. As shown in Figure 7(a), the blue circle (flat) indicates a safe state (contact force less than 2 N), the yellow circle (small dots) indicates a caution (contact force between 2 and 6 N), and the red circle (cross hatching) indicates an emergency warning (contact force more than 8 N). Figure 7(b) shows an example of the operation when the contact force was 3 N and the indicator turns yellow (small dots). Figure 7(c) shows an example of an emergency operation when the contact force was 10 N, and the indicator turns red (cross hatching). As part of future research, the system should be able to detect the contact even if the shaft is in contact with the skin.

5. **Conclusion.** In this study, we studied how to detect the contact of a robotic forceps on an organ in surgical operations. We measured the acceleration at two points on the shaft and estimated the transfer function between these points. For detecting the shaft contact, we selected a frequency band that changed when the shaft pressed on the organ. Therefore, the contact force of the shaft on a pseudoorgan could be estimated from the magnitude change within a specific frequency band. Using these results, we developed a prototype of the contact detection system which discriminated the contact force into three patterns: safe (less than 2 N), caution (from 2 to 6 N) and emergency (more than 8 N).



(a) 0 N (no contact) (b) 3 N (c) 10 N

FIGURE 7. Examples of the operation view of the prototype system when the shaft is in contact with the pseudo-organ

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