Study on Multi-DOF Ultrasonic Actuator for Laparoscopic Instrument*

Shinsuk PARK**, Kenjiro TAKEMURA*** and Takashi MAENO**

In surgical robots, compact manipulators with multi-degree-of-freedom (DOF) are essential owing to a small work volume in the patient body. Conventional single-DOF actuators such as electromagnetic motors require a multiple number of actuators to generate multi-DOF motion, which in turn results in bulky mechanism combined with transmission device. Our previous work has developed a compact ultrasonic motor capable of generating a multi-DOF rotation of a spherical rotor utilizing three natural vibration modes of a bar-shaped stator. The present study designs and builds a novel multi-DOF master-slave system for laparoscopic surgical procedures, using a single ultrasonic actuator. The system consists of surgical forceps on multi-DOF wrist with joystick controller. Experimental results have confirmed high responsiveness and precise position control of the master-slave system.

Key Words: Ultrasonic Motor, Minimally Invasive Surgery, Laparoscopic Forceps

1. Introduction

Recent robotic technology has been rapidly gaining acceptance in the operation room. Robots are known to enhance surgery by improving precision, repeatability, stability, and dexterity. Surgical robots are now regularly used in minimally invasive surgery (MIS). For example, ZEUS system from Computer Motion, Inc. and da Vinci system from Intuitive Surgical, Inc. are commercially available surgical robotic systems for MIS procedures. Besides robotic systems, other studies have developed multi-DOF laparoscopic surgical instruments with sophisticated mechanisms^{(1),(2)}.

Compared with open surgery, minimally invasive surgery is carried out using long instruments inserted into the patient's body through small (~ 1 cm) incisions with the surgeon manipulating the tool handles from outside the patient's body. Visual feedback is provided by an endoscope, a long tube inserted into the body, which sends back video images. This method results in reduced patient

pain and trauma, fewer complications, and shorter recovery periods. In minimally invasive surgery, however, small and dexterous surgical instruments are essential, which allows the surgeon to work through small incisions that are much smaller than would be required for human hands or to work at small scale⁽³⁾.

For dexterous manipulation, actuators capable of generating a sufficient number of DOF are desirable. Conventionally electromagnetic motors have been used to generate multi-DOF motion. With electromagnetic motors, however, the number of motors should be equal to or larger than the number of DOF, because electromagnetic motors can only generate single DOF rotational motion. Moreover, transmission mechanism to obtain larger torque makes the whole system bulkier and heavier.

Compared with electromagnetic motors, ultrasonic motors are known to have superior characteristics such as high torque capacity at low speed, high stationary limiting torque, low electromagnetic radiation and its simple structure. Many researchers have performed studies on multi-DOF actuators, utilizing the principle of ultrasonic motors. Bansevicius developed a piezoelectric multi-DOF actuator that consists of a cylindrical stator (vibrator) and a spherical rotor⁽⁴⁾. Amano *et al.* developed a multi-DOF ultrasonic actuator where a spherical rotor rotates along three perpendicular axes⁽⁵⁾. Toyama constructed a spherical ultrasonic motor that consists of three ring-shaped stators and a spherical rotor⁽⁶⁾. Sasae *et al.* developed a three-DOF motion unit consisting of a spherical rotor and truss

* Received 4th August, 2003 (No. 03-4102)

** Department of Mechanical Engineering, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama, Kanagawa 223-8522, Japan. E-mail: sspark@mech.keio.ac.jp, maeno@mech.keio.ac.jp

*** Precision and Intelligence Laboratory, Tokyo Institute of Technology, 4925 Nagatsuta-cho, Midori-ku, Yokohama, Kanagawa 226-8503, Japan.
E-mail: takemura@pi.titech.ac.jp

arranged piezoelectric ceramics⁽⁷⁾.

Though the ultrasonic motors mentioned above are capable of generating multi-DOF motion, they cannot replace general electromagnetic motors, due to their limited output torque, low controllability and difficulty in design. To enhance the performance of multi-DOF ultrasonic motor, precise geometric design of its stator and more sophisticated vibration control are necessary.

In our previous study, we have developed a new type of ultrasonic motor capable of generating multi-DOF motions⁽⁸⁾. The ultrasonic motor generates a multi-DOF rotation of a spherical rotor using three natural vibration modes of a bar-shaped stator, which is similar to the human wrist motion. The study has shown that the ultrasonic actuator of a compact size enables a dexterous manipulation.

This study proposes a novel surgical instrument with multi-DOF ultrasonic actuator for minimally invasive surgical procedures. The system is designed under the concept of master-slave position control system. First, we have developed a multi-DOF ultrasonic actuator. Then we have designed and implemented a master-slave surgical forceps system using real-time position control scheme. The performance of the system has been examined through experiments.

2. Multi-DOF Ultrasonic Motor

2.1 Driving principle

An ultrasonic motor is a frictionally driven motor. Generally it is composed of a stator (vibrator) and a rotor. The energy of vibration of the stator is transmitted to the rotor by the frictional force between the stator and the rotor. Most ultrasonic motors utilize two natural vibration modes of the stator to generate a single-DOF rotation of the rotor. By combining two vibration modes, points on the stator draw oval trajectories, and those trajectories, in turn, frictionally drive the rotor along a specific axis, while the rotor is in contact with stator. In our previous study, we have extended the idea to multi-DOF motion using three natural vibration modes with the directions of three vibration modes perpendicular to each other.

The multi-DOF ultrasonic motor we have developed consists of a bar-shaped stator and a spherical rotor as shown in Fig. 1. The spherical rotor rotates around three perpendicular axes by combining a first longitudinal vibration mode and two second bending vibration modes of the stator. The design requirements for the stator are as follows:

- i) Natural frequencies of three vibration modes are nearly identical.
- ii) Natural frequencies of three modes are low enough so that they do not excite undesirable higher vibration modes.
- iii) Motions driven by three vibration modes are per-

Fig. 1 Multi-DOF ultrasonic motor

Fig. 2 Driving principle

pendicular to each other.

Figure 2 shows the driving principle of the multi-DOF ultrasonic motor. The three axes (x , y , z) are defined as shown in Fig. 1. The rotor can rotate along the three perpendicular axes. Figure 2 (a) shows the natural vibration modes of the stator that drives the rotor along the z -axis. In the figure, the bending modes in the zx -plane and the yz -plane are denoted as (i)(iii) and (ii)(iv), respectively. The two modes are combined with a phase difference of 90 degrees so that the points in the stator head draw oval trajectories around the z -axis. The rotor in contact with the stator head rotates along the z -axis by frictional force applied by the stator. Figure 2 (b) illustrates the rotation of the rotor along the x -axis. In the figure, the longitudinal mode along the z -axis and the bending mode in the yz -plane, are denoted as (i)(iii) and (ii)(iv), respectively. The two modes are combined at a phase difference of 90 degrees so that the tip of the stator head drives the rotor along the x -axis by frictional force. The same principle applies when the rotor is driven around the y -axis; the longitudinal modes along the z -axis and the bending mode in the zx -plane are combined in the same way as in Fig. 2 (b).

2.2 Design and implementation

The geometry of the bar-shaped stator was designed using finite element analysis. As described in section 2.1,

Fig. 3 Geometry of multi-DOF ultrasonic motor

the stator was designed so that the natural frequencies of the first longitudinal and the second bending vibration modes correspond to each other. Figure 3 shows the developed multi-DOF ultrasonic motor. The diameter and height of the stator are 10 and 30.8 mm, respectively. The rotor has a spherical shape and is made of stainless steel. The bar-shaped stator consists of head, rings, stacked piezoelectric rings and a shaft. The stator head, rings, and shaft are made of nickel-plated brass, brass, and stainless steel, respectively. The shaft is screwed up into the head as in Langevin type vibrator. The piezoelectric ceramic rings are used to excite both the first longitudinal mode and the second bending modes of the bar-shaped stator. Preload between the stator and rotor is provided by the magnetic disk. The natural frequencies of the three vibration modes were measured to be around 40 kHz. The developed motor is capable of generating the maximum torque of 0.007 Nm.

2.3 Multi-DOF USM driver

The three vibration modes of the bar-shaped stator are driven by three sinusoidal input signals to piezoelectric actuators implemented in the stator. To drive the rotor along three axes as described in section 2.1, frequencies, amplitudes and phase shifts of three input signals are used as operating parameters, which adds up to the total number of nine parameters: three frequencies, three amplitudes, and three phase shifts:

$$\begin{cases} V_z = A_z \sin(2\pi f_z t + \phi_z) \\ V_x = A_x \sin(2\pi f_x t + \phi_x) \\ V_y = A_y \sin(2\pi f_y t + \phi_y) \end{cases} \quad (1)$$

Where,

V_z : Input signal for longitudinal vibration in z -direction

$V_{x,y}$: Input signals for bending vibrations in x - and y -directions

A_z : amplitude of input signal for longitudinal vibra-

Fig. 4 Multi-DOF USM driver circuit

tion

$A_{x,y}$: amplitude of input signals for bending vibrations

f_z : frequency of input signal for longitudinal vibration

$f_{x,y}$: frequencies of input signals for bending vibrations

ϕ_z : phase shift of input signal for longitudinal vibration

$\phi_{x,y}$: phase shifts of input signals for bending vibrations

The relationships among nine operating parameters, angular rotation and driving torque were determined in our previous study⁽⁸⁾. Figure 4 shows a schematic view of USM driver circuit. Three square wave signals are generated using function generator and phase shifters. To acquire sinusoidal signals at 40 kHz, the square waves pass through the low-pass filter with cutoff frequency at 40 kHz. The filtered signals, then, are amplified and applied to piezoelectric actuators of the stator.

3. Surgical Tools for Minimally Invasive Surgery

3.1 Design

In minimally invasive surgery, the surgical tool is placed through a small incision in the patient body. The incision port provides a pivot point that allows three-

dimensional rotational motion and one-dimensional translational motion. Figure 5 shows a conventional forceps for minimally invasive surgical procedures. Although there are several obvious advantages to using minimally invasive surgery compared to open surgery, surgeons face many challenges in making the shift. These include the issues inherent to endoscopic surgery of decreased visual and haptic information, significant motion constraints, and the need for cognitive spatio-motor remapping⁽¹⁾. This is where *surgical robots* come into play. The teleoperated surgical robots seek to alleviate some of these human factors issues by increasing the information available to the surgeon while maintaining the minimally invasive nature of the procedure.

Using the ultrasonic actuator developed in the previous section and teleoperation concept, we have designed a surgical forceps with multi-DOF wrist as shown in Fig. 6. The forceps consists of multi-DOF wrist joint with ultra-

(a) Conventional laparoscopic forceps

(b) Thoracic MIS procedure

Fig. 5 MIS procedure using conventional forceps

Fig. 6 Multi-DOF surgical forceps

sonic actuator, gripper, potentiometers, and joystick controller. In minimally invasive surgical procedures, the forceps is placed through a small incision in the patient body. In addition to the four-DOF global motion at the pivot point, three-dimensional angular position of the gripper can be controlled through joystick controller, under master-slave system control scheme.

3.2 Implementation

Based on the design described in the previous section, we have constructed a master-slave system of laparoscopic forceps. The prototype of the system is shown in Fig. 7. The controller of the system is implemented on a PC. Thumb-controlled SONY PlayStation joystick, which has two potentiometers, is used as master port, and the wrist of the forceps constitutes slave port. The angular positions of master and slave are measured using two potentiometers on the joystick and two potentiometers on the position sensing unit for multi-DOF ultrasonic motor. Figure 8 illustrates the position sensing unit of the wrist. The signals from the potentiometers of joystick and multi-DOF wrist are sent to the PC through A/D converter. Considering the driving principle described in section 2.1, three sinusoidal input signals to the multi-DOF ultrasonic motor are generated using USM driver circuit as shown in Fig. 9. Three square wave signals are generated in function generator and modulated in phase shifters, where both function generator and phase shifters are implemented on FPGA (Field Programmable Gate Array). As described in section 2.3, angular position of the wrist is controlled by modulating three sinusoidal signals. While three frequencies, three amplitudes, and three phase shifts of the three signals can be used as operating parameters, only the amplitudes and phases for the two bending modes are modulated to control angular position of the wrist along x - and y -directions.

To control angular position of the wrist, the amplitudes were controlled using proportional controller, and the phase shifts were modulated, while the frequencies were kept at around 40 kHz:

• Longitudinal Vibration (z -direction)

$$\text{Amplitude: } A_z = 20[V] = \text{const.} \quad (2)$$

$$\text{Phase: } \phi_z = \pi/2 = \text{const.} \quad (3)$$

• Bending Vibration (x -direction)

$$\text{Amplitude: } A_x = K_p |\theta_y - \theta_y^d| + \varepsilon \quad (4)$$

$$\begin{aligned} \text{Phase: } \phi_x &= 0 & (\theta_y - \theta_y^d < 0) \\ &= \pi & (\theta_y - \theta_y^d > 0) \end{aligned} \quad (5)$$

• Bending Vibration (y -direction)

$$\text{Amplitude: } A_y = K_p |\theta_x - \theta_x^d| + \varepsilon \quad (6)$$

$$\begin{aligned} \text{Phase: } \phi_y &= 0 & (\theta_x - \theta_x^d < 0) \\ &= \pi & (\theta_x - \theta_x^d > 0) \end{aligned} \quad (7)$$

Where,

(a) Master-slave forceps system

(b) Master port

Multi-DOF ultrasonic motor

Potentiometer

(c) Slave port

Fig. 7 Prototype of master-slave forceps system

K_p = proportional gain

θ_x, θ_y = angular displacements of slave

θ_x^d, θ_y^d = angular positions of master

ε = bias.

The controller for master-slave system was developed using Turbo C++ on MS-DOS. Real-time control with

Fig. 8 Multi-DOF position sensing unit

Fig. 9 Master-slave forceps system

timer interrupt of 2 ms interval was used for the master-slave controller.

4. Experiments

4.1 Human finger motion

As a precursor study for master-slave system design, the characteristics of human finger motion were examined through experiments. To measure the bandwidth of human finger motion, four human subjects were instructed to make a series of sharp jerky motions of the thumb. The subjects were all male affiliated with Keio University, ranged in age from 23 to 36. They were informed that the amplitude of their movements was not important but that they should attempt to make their movements as abrupt as possible. It was reasoned that an impulse as an extremely abrupt movement would include the highest frequency components that the subject was capable of producing. Thus, power spectral density was used as an estimation of the bandwidth of finger motion. Figure 10(a) illustrates the thumb displacement from one subject during impulsive motion. Rise times were typically between 80 and 100 milliseconds. Figure 10(b) shows the power spectral density of the displacement, where the unit of power spectral density is arbitrary. As can be seen in the figure, the power spectral density tails off rapidly around 10 to 20 Hz for all the subjects. The human finger bandwidth between 5 to 15 Hz would indicate a minimum bandwidth of master-slave system should be faster than 15 Hz. It was

(a) Impulsive finger motion

(b) Power spectral density

Fig. 10 Impulsive finger motion and its power spectral density function

reported that the bandwidth of human *arm* motion is between 20 and 30 Hz⁽⁹⁾.

4.2 Master-slave system responses

The performance of master-slave system was tested through step response experiment and cross-correlation analysis. Figure 11 shows the step response of the spherical rotor along the *x*-axis, where a target position is set at 10 degrees. The rise time of the step response was around 35 ms.

The bandwidth of the master-slave system was estimated from slave response to impulsive master input. Figure 12 shows power spectral density function of slave response. The figure shows much higher bandwidth of the master-slave system than finger motion. The response of master-slave system appears to be much faster than human finger motion, which has the bandwidth lower than 15 Hz.

Cross-correlation of master input and slave output were calculated to determine the responsiveness of master-slave system. With impulsive input at master, the location

Fig. 11 Step response (solid line: reference, dotted line: measured)

Fig. 12 Power spectral density function of impulsive response of master-slave system

of peak point of cross-correlation function can be used as an index of time delay between master input and slave output. As can be seen in Fig. 13, the peak points of cross-correlation functions were around 70 milliseconds, which indicates that there was about 70-millisecond delay between impulsive master input and slave output. Figure 14 illustrates history plots of slave output with arbitrary master input, where two angular displacements along *y*- and *x*-axes were controlled simultaneously. The response delays of the electro-mechanical system presented in this study probably result from slipping between stator and rotor, as well as computational delays from the control routine.

5. Discussion

Surgical robots promise to become the standard modality for many common procedures. At this point, the primary benefit of robot surgery would be less trauma to the patient's body because it enables minimally invasive procedures resulting in faster recovery time. Robot

Fig. 13 Cross-correlation function of impulsive master input and slave output

Fig. 14 Time history of multi-DOF control of master and slave

surgery, however, has the limitation in dexterity as in conventional laparoscopic surgery. Dexterous manipulation in a small space, as in the patient body, requires compact actuators that generate a sufficient number of DOF. For minimally invasive procedures, ultrasonic actuator may be one of the best candidates due to its compact size and high torque characteristics at low speed.

This paper developed a new master-slave surgical forceps using the multi-DOF ultrasonic motor. The developed master-slave system is controlled using real-time position control scheme. The responsiveness of the system has been examined through experiments and compared with human finger motion. The results indicate that the response of the master-slave system is fast enough compared to human operator's finger motion.

6. Conclusions and Recommendations

Our previous study has developed an ultrasonic motor capable of generating multi-DOF motions. This study pre-

sented a novel surgical forceps for minimally invasive surgical procedures, using the developed actuator. The main results of this paper are as follows:

- Using the ultrasonic actuator, we have developed a new master-slave system for multi-DOF laparoscopic forceps.
- The master-slave system allows us to control the multi-DOF wrist motion with thumb-controlled joystick.
- Real-time position control scheme of the system enables fast and precise position control of USM.

Recently, intra-operative Magnetic Resonance Imaging (MRI) has become significant clinical procedure for minimally invasive surgery, where common mechanical parts cannot be used in MR environment because they usually contain ferromagnetic material⁽¹⁰⁾. It is noteworthy that the ultrasonic motor does not affect the magnetic field of Magnetic Resonance Imaging (MRI), since it does not require coil or magnet as its driving source. In the multi-DOF ultrasonic actuator developed in this study, preload between the stator and rotor is given by magnetic disc. To be compatible in MR environment, preload may be applied using elastic or piezoelectric material, in place of the magnetic component.

Acknowledgment

This work was supported by JSPS. This support is gratefully acknowledged.

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