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[N396] Development of Multi-DOF Ultrasonic Actuators for Surgical Tools

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Abstract

Over the past decade, robotic technology has been rapidly gaining acceptance in the operation room. In robotic surgery, compact manipulators with multi-degree-of-freedom (DOF) are essential owing to a small work volume in the patient body. To generate multi-DOF motion, single DOF actuators such as electromagnetic motors have been conventionally used. That, however, requires multiple actuators, which in turn results in bulky mechanism combined with reduction device. In recent years, various compact multi-DOF actuators have been proposed and developed. Among them ultrasonic motors have become popular due to its simple structure and high torque capacity.

Our previous work developed an ultrasonic motor capable of generating a multi-DOF rotation of a spherical rotor using three natural vibration modes of a bar-shaped stator. This study develops a novel multi-DOF master-slave system for surgical procedures using the single ultrasonic motor. The system consists of surgical forceps on multi-DOF wrist with joystick controller. Experiments have confirmed high responsiveness of the master-slave system with real-time position control scheme.

Keywords: Ultrasonic motor, Minimally Invasive Surgery

1. Introduction

Over the past decade robots have been appearing in the operation rooms. Robotic technology enhances surgery by improving precision, repeatability, stability, and dexterity. Surgical robots are now regularly used in minimally invasive surgery. In minimally invasive surgery, the entire surgical procedure 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 incisions that are much smaller than would be required for human hands or to work at small scale.

Dexterous manipulation requires actuators that are capable of generating a sufficient number of DOF. 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, since 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 at low speed, high stationary limiting torque, low electromagnetic radiation and its simple structure. Many researchers have performed studies on multi-DOF actuators, using the principle of ultrasonic motors. Bansevicius developed a piezoelectric multi-DOF actuator that consists of a cylindrical stator (vibrator) and a spherical rotor [1]. Amano et al. developed a multi-DOF ultrasonic actuator where a spherical rotor rotates along three perpendicular axes [2]. Toyama constructed a spherical ultrasonic motor that consists of three ring-shaped stators and a spherical rotor [3]. Sasae et al. developed a three-DOF motion unit consisting of a spherical rotor and truss arranged piezoelectric ceramics [4].

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

In our previous study, we have developed a new type of ultrasonic motor capable of generating multi-DOF motions [5]. 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 developed actuator enables a dexterous manipulation with compact motion unit.

This study proposes a novel forceps system for minimally invasive surgical procedures with multi-DOF ultrasonic actuator. 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 using real-time position control scheme. The performance of the system has been tested 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.

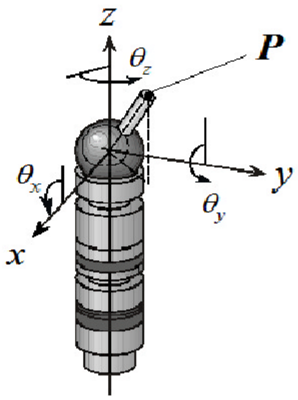

Fig.1. Multi-DOF ultrasonic motor.

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 unwanted higher modes.
- iii) Motions of three vibration modes are perpendicular to each other.

Fig. 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. Fig. 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 tip of the stator head rotates around the *z*-axis. The rotor in contact with the stator head rotates along the *z*-axis by frictional force. Fig. 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 rotates around the *x*-axis. The rotor, in turn, rotates along the *x*-axis due to 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).

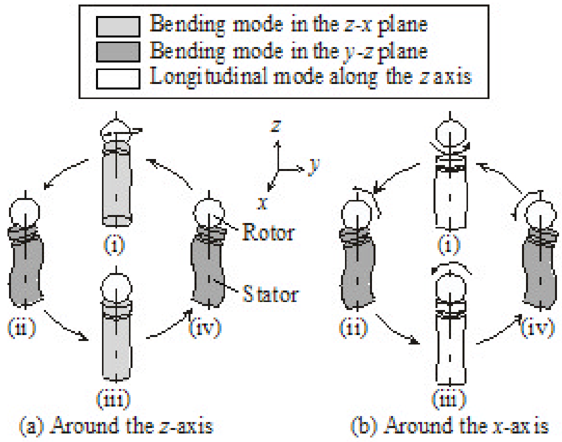

Fig. 2. Driving principle

2.2 Design and Implementation

The geometry of the bar-shaped stator was designed using finite element analysis. As mentioned in section 2.2, 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 multi-DOF ultrasonic motor developed in our previous study. The diameter and height of the stator are 10 and 31.85 mm, respectively. The rotor has a spherical shape 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 applied by the magnetic disk. The natural frequencies of the three modes were measured to be around 40 kHz. The developed motor generates the maximum torque of 7 mNm.

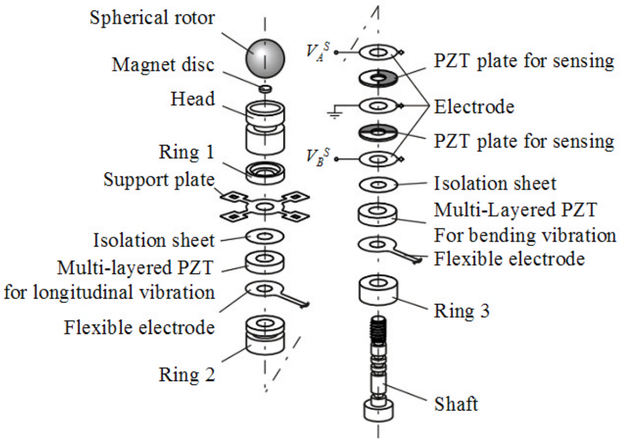

Fig. 3. Geometry of multi-DOF ultrasonic motor.

3. Multi-DOF Surgical Forceps

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. Fig. 5 shows a conventional forceps for minimally invasive surgical procedures. Using the ultrasonic actuator developed in the previous section, we have designed a surgical forceps as shown in Fig. 4. The forceps consists of multi-DOF wrist joint with ultrasonic 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.

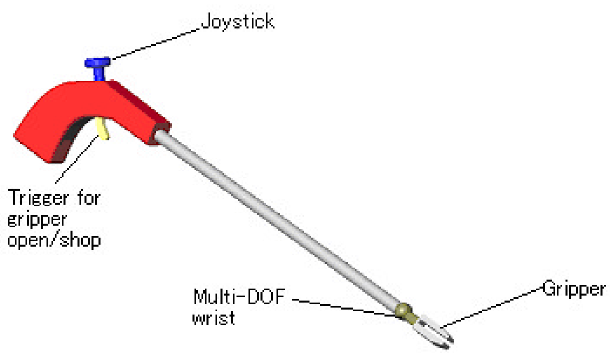

Fig. 4. Multi-DOF surgical forceps.

3.2. Implementation

In this study, we have constructed a master-slave system for the surgical forceps. The prototype of the system is shown in Fig. 5. The system is controlled using a PC. PlayStation joystick, which is thumb-controlled, is used as master port, and the wrist of the forceps constitutes slave port. The angular positions of master and slave are measured using four potentiometers. The signals from potentiometers of master and slave are sent to the PC through A/D converter. Three A/C input signals for the multi-DOF ultrasonic motor are generated using function generator and phase shifters, considering the driving principle described in section 2. Angular position of the wrist is controlled by modulating three A/C input signals. Frequencies, amplitudes, and phase shifts of A/C input signals can be used as operating parameters. In the present paper, the amplitudes and phases for the two bending modes are modulated to control rotations of the wrist along x- and y-directions.

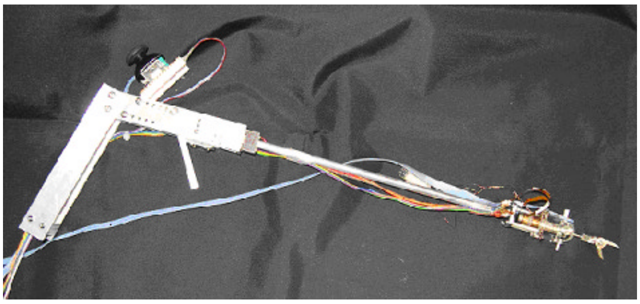

Fig. 5. Prototype of master-slave forceps system.

To control angular position of the wrist, the amplitude is controlled using proportional controller and the phase shift are changed as Equations (1) to (6), while the frequencies were kept at around 40 kHz.

Longitudinal Vibration (z-direction)

Amplitude : $V_z = 20$ [V] = const. (1)

Phase : $\phi_z = \pi/2$ = const. (2)

Bending Vibration (x-direction)

Amplitude : $V_x = K_p \,|\, \theta_y - \theta_y{}^d \,| + \varepsilon$ (3)

Phase : $\phi_x = 0 \quad (\theta_y - \theta_y{}^d \geqq 0)$

$= \pi \quad (\theta_y - \theta_y{}^d \leqq 0)$ (4)

Bending Vibration (y-direction)

Amplitude : $V_y = K_p \,|\, \theta_x - \theta_x{}^d \,| + \varepsilon$ (5)

Phase : $\phi_y = 0 \quad (\theta_x - \theta_x{}^d \geqq 0)$

$= \pi \quad (\theta_x - \theta_x{}^d \leqq 0)$ (6)

Where,

V_z = amplitude of input signal for longitudinal vibration

$V_{x,y}$ = amplitude of input signals for bending vibrations

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

4. Experiments

The performance of master-slave system was tested through step response experiment and cross-correlation analysis. Fig. 6 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 30 ms. High frequency components shown in the figure seems to result from noises at potentiometers.

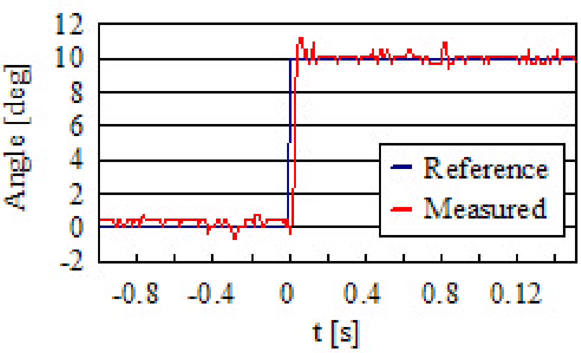

Fig. 6. Step response.

Cross-correlation of master input and slave output were calculated to determine the responsiveness of master-slave system. With impulsive input, the location of peak point of cross-correlation function can be used as an index of time delay between input and output. The peak points of cross-correlation functions were around 0 sec, which indicates that there was no significant delay in slave motion.

5. Conclusions

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 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.

Our previous study has developed an ultrasonic motor capable of generating multi-DOF motions. The ultrasonic motor generates a multi-DOF rotation of a rotor using three natural vibration modes of a stator.

In this study, we have developed a new master-slave surgical forceps using the multi-DOF ultrasonic actuator developed in our previous study. The master-slave system is controlled using real-time position control scheme. The responsiveness of the system has been confirmed through experiments.

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. Since the ultrasonic motor does not require coil or magnet as its driving source, it does not affect the magnetic field of Magnetic Resonance Imaging (MRI). The surgical forceps developed in this study may also be used in MR environment.

6. References

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