Compact Forceps Manipulator Using Friction Wheel Mechanism and Gimbals Mechanism for Laparoscopic Surgery

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Abstract. This paper reports evaluation of compact forceps manipulator designed for assisting laparoscopic surgery. The manipulator consists of two miniaturized parts; friction wheel mechanism which rotates and translates forceps ($62\times52\times150$[mm^3], 0.6[kg]), and gimbals mechanism which provides pivoting motion of forceps around incision hole on the abdomen ($135\times165\times300$[mm^3], 1.1[kg]). The four-DOF motion of forceps around the incision hole on the abdomen in laparoscopic surgery is realized. By integration with robotized forceps or a needle insertion robot, it will work as a compact robotic arm in a master-slave system. It can also work under numerical control based on the computerized surgical planning. This table-mounted miniaturized manipulator contributes to the coexistence of clinical staffs and manipulators in the today's crowded operating room. As the results of mechanical performance evaluation with load of 4 [N], positioning accuracy was less than 1.2 [deg] in pivoting motion, less than 4 [deg] in rotation of forceps, less than 1.2 [mm] in longitudinal translation of forceps. As future works, we will modify mechanism for sterilization and safety improvement, and also integrate this manipulator with robotized forceps to build a surgery assisting robotic system.

1 Introduction

Today, as a means of minimally invasive surgery, laparoscopic surgery is widely performed. Surgeons cut small holes on the abdomen to insert laparoscope and forceps, and conduct all operations inside the abdominal cavity. Small incisions damage patients much less than conventional laparotomy, and patients can get relief from postoperative pain or medication. This patient-friendly technique, however, is rather difficult and cannot be applied to all cases, mainly because the limited degrees of freedom (DOF) of forceps eliminate the dexterity of surgeons (Fig.1(a)). Surgeons must take special training for laparoscopic surgery.

Responding to these issues, surgery-assisting robotic manipulators are developed. Some of them are clinically applied and show their availability [1,2]. Those new systems have provided surgeons with technologically advanced hand skills,

J. Duncan and G. Gerig (Eds.): MICCAI 2005, LNCS 3750, pp. 81–88, 2005.

and enabled higher-quality and more precise operation, that could not be realized in the conventional laparoscopic surgery. Meanwhile, the large size of them caused problems. Some robotic systems require larger room and are difficult to install into conventional crowded operating theater. As the operation space above the patient's abdomen is occupied by the manipulator arms, clinical staffs have troubles to observe the patient and have danger of collision with manipulators. Thus, a new compact surgery-assisting robotic system is required [3].

We have developed a compact forceps manipulator using "friction wheel mechanism" (FWM) [4] and gimbals mechanism (Fig. 1(b)). In the former study, a prototype was manufactured, and feasibility was shown as a forceps manipulator [5]. At the same time, some problems emerged. The rotational speed of ultrasonicmotor varied depending on various factors, that is, the motor we adopted for actuation was unstable, being affected by temperature and load, so that the motion of forceps was also unstable under the open-loop controlling system [6]. In the recent presentation [7], we reported mechanical implementation of miniaturized ultrasonic motors with rotary encoder into the mechanically-modified prototype, and reported evaluation of basic performance using feedback control system. Positioning accuracy of the gimbals mechanism was less than 0.6 [deg], and that of friction wheel mechanism was less than 0.2 [mm] in translation and 1 [deg] in rotation.

In the former studies, the accuracy was measured as a static positioning device without load. Thus, in this study, we measured and evaluated static position accuracy with load of 4 [N]. In section 2, we introduce the configuration and mechanism of our compact forceps manipulator. Experimental apparatus and evaluation results are shown in section 3. We discuss the results of performance evaluation in section 4. Conclusions are presented in section 5.

2 System Configuration

We adopted following two mechanisms to realize four-DOF motion of forceps required in laparoscopic surgery(Fig.1(a)); "Friction wheel mechanism" (FWM) provides the rotation around the forceps shaft and translation along the shaft (number (1) and (2) in Fig.1(b)). Gimbals mechanism realizes the pivoting motion to determine the direction of the forceps (number (3) and (4) in Fig.1(b)). The dimension of the FWM is $62\times52\times150[\mathrm{mm}^3]$ and the weight was 0.6[kg]. Those of gimbals mechanism are $135\times165\times300[\mathrm{mm}^3]$ and 1.1[kg]. We mount this manipulator near the incision hole using multiple joint arm (ex. Iron intern$^{(R)}$ [8] or Point setter [9]). This is because mechanisms and actuators should be mounted near the operating field so that they require less torque or force [3].

Friction wheel mechanism (FWM) consists of three titled idle rollers and outer case (Fig. 2(a)). Three idle rollers around the forceps shaft travel spirally on the surface of shaft when outer case rotates (Fig. 2(b)) [10]. A couple of FWMs with opposite tilting angle (like right-handed screw and left-handed one) hold the forceps shaft(Fig. 2(c)). When they rotate in the same direction, the shaft held statically by rollers rotates around its longitudinal axis (Fig. 3(a)).

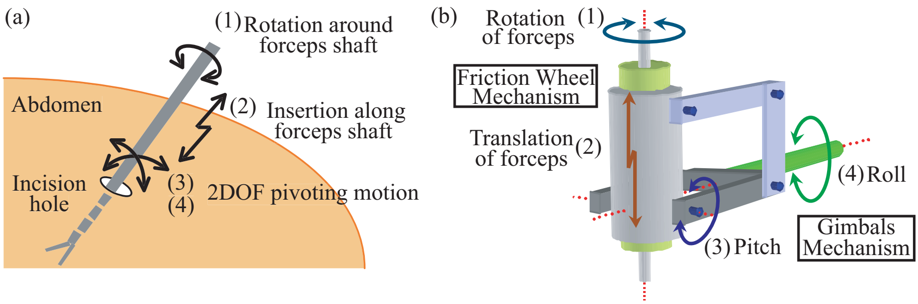

Fig. 1. System configuration, (a) In laparoscopic surgery, forceps have only four degrees of freedom; two for rotation(1) and insertion(2) of forceps, two for pivoting motion(3)(4) around the incision hole. (b) Friction Wheel Mechanism provides two motions of (1) and (2). Gimbals mechanism realizes the rotational motions of (3) and (4).

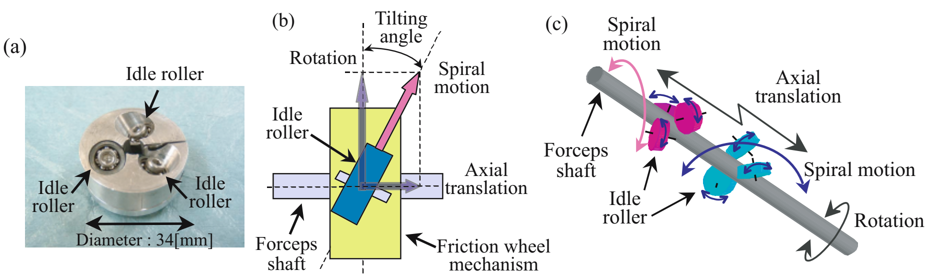

Fig. 2. Friction wheel mechanism, (a) a FWM has three rollers (arrow). (b) Rollers travel spirally on the surface of shaft. That motion can be divided into axial translation along the shaft and rotation around the shaft. (c) We combine two different spiral motions to realize rotation and translation.

Alternatively, when they rotate in the opposite direction, rollers travel on the shaft spirally and rotational motion is cancelled by rotational component of each spiral motion, so that forceps moves along its axis (Fig. 3(b)). The tilting angle was set at 30 [deg] in this study. We used hollow-shaft ultrasonic motors with rotary encoder (custom order, Fukoku, Japan) to drive the outer case of FWM for miniaturization of the system. The resolution of the rotary encoder was 0.2 [deg/pulse].

Gimbals mechanism provides pivoting motion, two rotational motions around the mutually-perpendicular axes. It is to be noted that pivot center of this manipulator is not located at the incision hole, but at the intersectional point of two axes. As for a surgery assisting robot for laparoscopic surgery, "remote center of motion (RCM)" mechanism should be mounted to bind the rotational center of manipulator at the incision hole (ex,[11,12]). However, as we reported in [5], it is not always necessary. This was because abdominal muscle under anesthesia gets flaccid and manipulator does not damage the abdominal wall by driving the

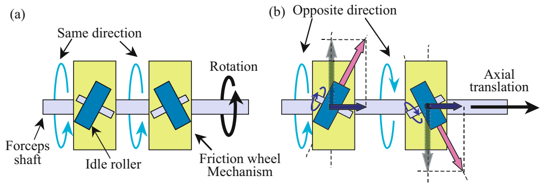

Fig. 3. Driving mechanism of forceps, (a) Rotation, (b) Translation

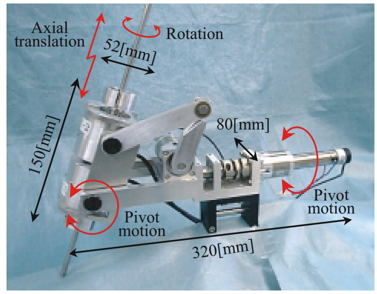

Fig. 4. New prototype

forceps. We used geared DC servomotors (ENC-185801, Chiba Precision Co.,Ltd, Japan) for actuation. The reduction gear ratio was 1/576. The resolution of the rotary encoder was 0.36[deg/pulse]. The prototype is shown in Fig. 4.

3 Evaluation Experiments

We conducted mechanical performance evaluation of our forceps manipulator. In the former studies, we conducted performance evaluation without any load [5,6,7]. Thus, in this study, we applied a load of 4[N], that was equivalent to the one third weight of Japanese male liver.

We measured working range and positioning accuracy of each axis (pitch and roll motions in gimbals mechanism, rotation and longitudinal translation of forceps in FWM) with load. Motion of manipulator was recorded using digital microscope (VH-7000C, KEYENCE, Japan), and working range and positioning

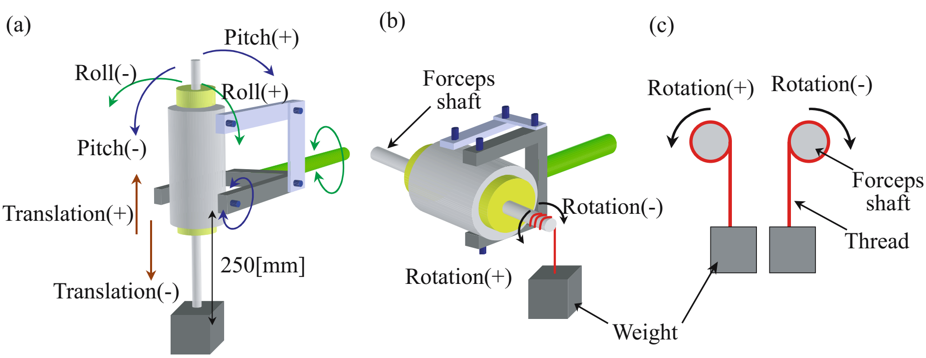

Fig. 5. Experimental setup, (a) Forceps were initially set in the vertical position to measure the motion of gimbals mechanism and the translation. Input direction is defined as shown here. (b) In the evaluation of rotation, forceps were set horizontally. (c) We measured the rotational positioning accuracy of forceps when forceps were pulling up the weight.

accuracy were measured by its accompanying utility software. Each measurement was repeated for twelve times. In order to reduce the measuring error, maximum and minimum values were eliminated, and the average and standard deviation of other ten values were calculated. Positive value in positioning error means that manipulator overruns beyond the input command, and negative means that it does not reach the goal. The definition of +/- input direction is shown in Fig. 5. As the initial setting, the forceps were set vertically in the evaluation of gimbals mechanism and translation of forceps (Fig. 5(a)), and horizontally in rotation (Fig. 5(b)). The distance between the weight and the center of gimbals mechanism was 250 [mm].

3.1 Gimbals Mechanism

Working range of gimbals mechanism was measured. No decrease of working range was shown (Table. 1). Positioning accuracy of the gimbals mechanism was measured at every 5 [deg] from -30 [deg] to $+30$[deg]. Measurement results are shown in Fig.6, comparing the results of evaluation without load [7]. Accuracy was less than 1.2 [deg] in pitch and roll motions.

3.2 Friction Wheel Mechanism (FWM)

As for the working range, FWM has no mechanical limitation, and the load did not limit the working range (Table. 1).

Before measuring the positioning accuracy, we evaluated the separation of rotation and translation. Because rotation and translation of forceps are generated by combining a couple of spiral motions, if each spiral motion differs from each other because of machining error, rotational error occurs in translation and translational error occurs in rotation [7,13]. Thus we measured the motion error beforehand and added compensation factor. When 45 [mm] translation command (that corresponds to 5 revolutions or 1800[deg] rotation of friction wheel) was input, forceps rotated 14.3 [deg]. This means that the difference of rotational traveling distance between FWMs is 14.3 [deg]. Thus we applied two coefficients; 1 - (14.3 / 1800) to longer traveling one, and 1 + (14.3 / 1800) to shorter traveling one.

Positioning accuracy of FWM was measured at every 45 [deg] from -180 [deg] to $+180$[deg] in rotation, and at every 20[mm] from -80 [mm] to $+80$[mm]

Table 1. Results of Working Range Evaluation

	Working Range	
	with load	w/o load
Pitch [deg]	-35.0 – $+37.0$	-35.0 – $+37.0$
Roll [deg]	$\pm$ 180.0	$\pm$ 180.0
Rotation [deg]	no limitation	no limitation
Translation [mm]	no limitation	no limitation

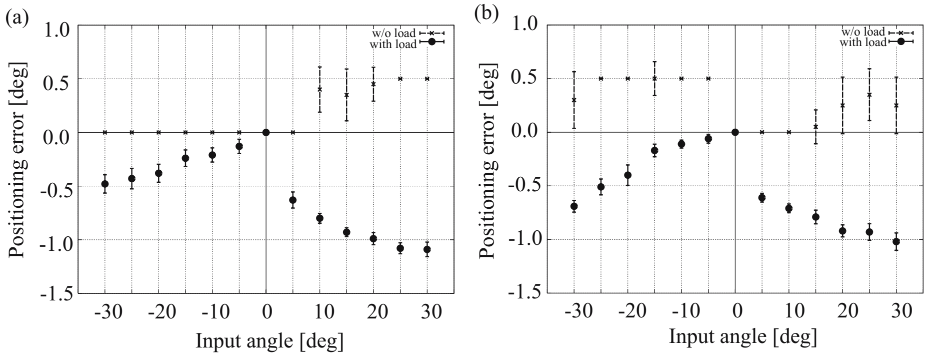

Fig. 6. Positioning accuracy of gimbals mechanism, (a) Pitch, (b)Roll

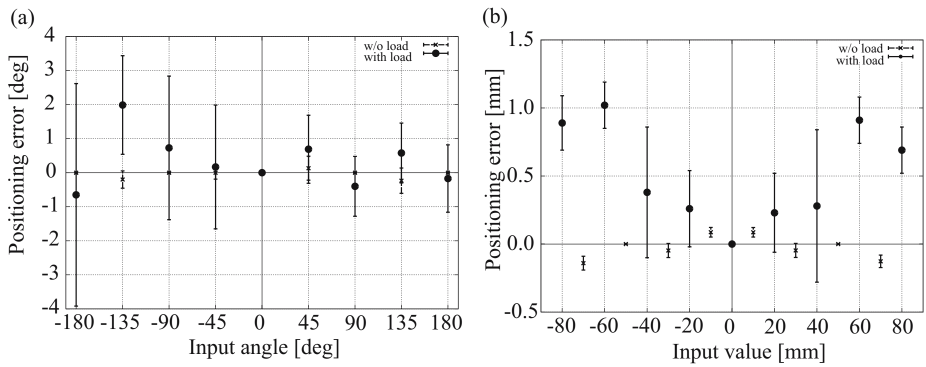

Fig. 7. Positioning accuracy of friction wheel mechanism, (a) Rotation, (b) Translation

in translation. The diameter of the forceps was 5 [mm], thus the torque applied by the weight was 10 [mNm]. Results are shown in Fig. 7. The accuracy was less than 4 [deg] in rotation of forceps, less than 1.2 [mm] in longitudinal translation.

4 Discussion

4.1 Working Range and Positioning Accuracy

Working range of gimbals mechanism and FWM did not affected by the load of 4 [N]. As for the roll motion of gimbals mechanism and rotation and translation of FWM, they have no mechanical limitation to realize wide range of motion. However, we can think mechanical limitation is desirable to ensure the safety in the case of malfunction. Some kind of safety mechanism should be implemented without wasting the advantages of gimbals mechanism and FWM.

As for the positioning accuracy of gimbals mechanism, it decreased as the input value increased. However, results showed the relative small standard deviation and high repeatability, thus high positioning accuracy will be realized by adding offset into input command depending on the load.

Positioning accuracy of FWM also decreased, especially in the rotation of forceps. This would be because the friction force between idle roller and forceps shaft to hold the forceps is smaller than external force by the load. Though we used stainless steel for idle rollers and shaft from the viewpoint of future washing and sterilization in the current prototype, we have to consider other materials to strengthen the friction force.

4.2 Future Works

We have following plans as near-term future works.

1. We will measure the dynamic response characteristics with/without load. The dynamic characteristics must be known to drive this manipulator smoothly as a slave robotic arm in a master-slave system.

2. As a related work, we evaluated the tilting angle of idle rollers in FWM [15]. In that study, FWM with rollers of 45 [degree] tilting angle showed higher speed, torque and force, and did not show any decrease in the positioning accuracy, comparing with those of 30 [degree], those were used in this study. Thus we will replace the FWMs with new ones.

3. Sterilization-compatible mechanism should be implemented for the clinical application. We will use “separation method” that separates sterilized and non-sterilized part via transmission part [14].

5 Conclusion

In this study, we evaluated the compact forceps manipulator using gimbals mechanism and FWM. As the results of experiments applying 4[N] load, positioning accuracy of the gimbals mechanism was less than 1.2 [deg], and that of friction wheel mechanism was less than 4 [deg] in rotation and 1.2 [mm] in translation.

This manipulator can work as a compact robotic arm to manipulate various kinds of forceps, ex. wire-driven bending forceps [16], bending forceps using linkage mechanism [17], and laser surgical tool [18], or rigid laparoscope can be manipulated with this system. In other words, this manipulator can be a common platform for robotized forceps. Thus we are going to integrate various surgical instruments with this manipulator to use robotized sophisticated surgical equipments.

Acknowledgement

This work is partially supported by “Research for the Future Program (JSPS-RFTF 99I00904)” funded by Japan Society for the Promotion of Science, Electro-Mechanic Technology Advancing Foundation, “Research and Development of the Compact Surgical Robot System for Future Medical Care” funded by New Energy and Industrial Technology Development Organization (NEDO), and “Research on medical devices for analyzing, supporting and substituting the function of human body” funded by Ministry of Health, Labour and Welfare.

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