Mechanical error analysis of compact forceps manipulator for laparoscopic surgery

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1. Introduction

Laparoscopic surgery, sometimes called "keyhole surgery", is one of minimally invasive surgical techniques. All procedures are completed inside abdominal cavity through 3–4 small holes on the abdomen using rigid thin videoscope and long-handled surgical instruments such as clamp, scissors, and scalpel. This patient-friendly technique has a lot of merits compared with conventional laparotomy; less pain, shorter hospital stay, and lower medical costs. It is, however, a difficult procedure. As the linear-shape forceps are bound at the incision hole, symmetrical motion is required around the fulcrum. Surgeons have only four Degrees of Freedom (DOF); two DOFs are for the orientation of forceps, and the other two for axial rotation and longitudinal translation of forceps (Fig. 1), so that laparoscopic surgery needs highly-skilled surgeons with enough experiences.
As one of engineering solutions responding to these clinical issues, surgical manipulators are developed and some of them, such as da Vinci® Surgical System, are clinically applied. These manipulators are aiming to enhance surgeons' ability and dexterity, not for automatic robot surgery. While great contribution to high-quality surgical procedure using three-dimensional view and dexterous robotic hands, one of the drawbacks of surgical manipulators is their size. Conventional operating theatre is too small to install the robotic surgery system. Thus, space-saving, miniaturized manipulator is required.

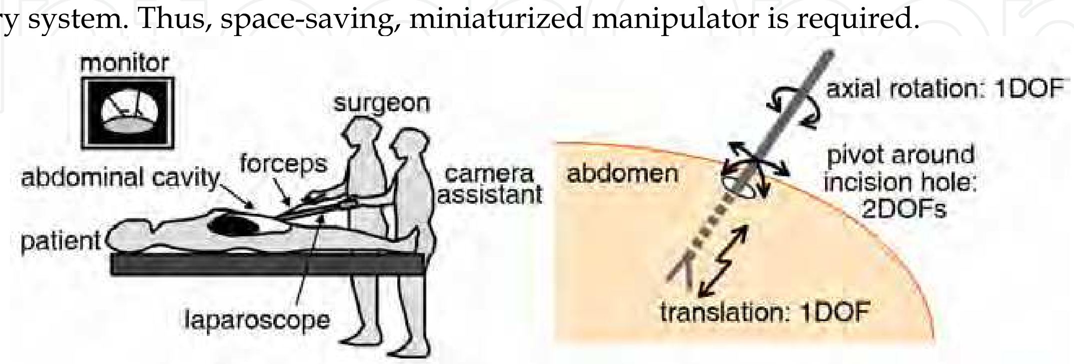

Figure 1. Laparoscopic surgery; surgeon manipulates forceps watching video from laparoscope controlled by camera assistant (left). Limitation of degrees of freedom (rotation, translation, and pivot) is one of causes that make laparoscopic surgery difficult for surgeon (right)

Source: Medical Robotics, Book edited by Vanja Bozovic, ISBN 978-3-902613-18-9, pp.526, I-Tech Education and Publishing, Vienna, Austria

We have developed a compact forceps manipulator using "friction wheel mechanism" (FWM) and "gimbals mechanism" (Suzuki, et al., 2002) and evaluated it (Suzuki, et al., 2005). In this paper, we 1) introduce the mechanism of the manipulator and 2) describe the mathematical analysis of the mechanical error and correction factor based on mechanism of manipulator and the measured error.

2. Method

2.1 Mechanical configuration

In laparoscopic surgery, at least four DOFs are required for forceps motion: axial rotation and longitudinal translation of the forceps, and pivot motion around the incision hole on the abdomen (Fig. 1). We realize only four DOFs because redundancy may disturb the miniaturization and simplification of mechanism; those are important factors for clinical application and commercialization. The compact forceps manipulator we have developed consists of two mechanical subcomponents; Friction Wheel Mechanism (FWM) and Gimbals mechanism. The FWM provides axial rotation and longitudinal translation of forceps using friction drive mechanism. Gimbals mechanism realizes pivot motion of forceps. The prototype is shown in Fig. 2. Dimensions of manipulator are 80×150×320 mm^3 and weight is 1.7 kg.

2.2 Friction wheel mechanism

Friction wheel mechanism consists of a couple of friction wheel that has three tilted driving rollers and outer case (Fig. 3).

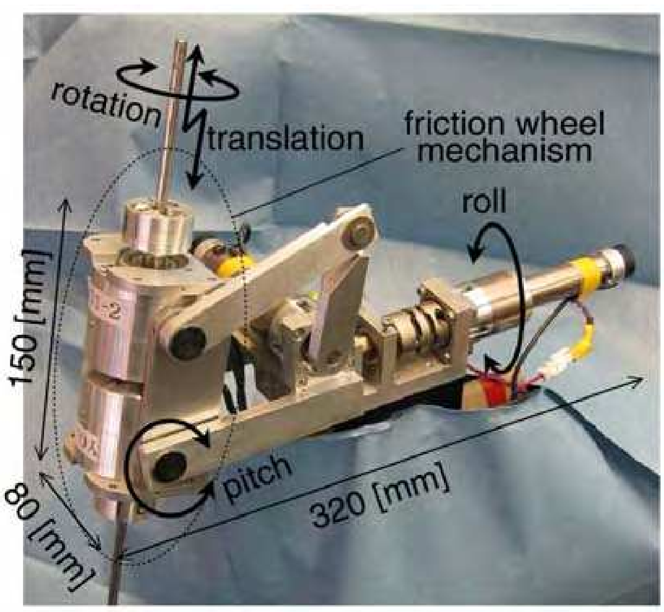

Figure 2. Prototype of compact forceps manipulator; friction wheel mechanism provides rotation and translation of forceps, gimbals mechanism realizes pivot motion (roll, pitch)

Three rollers are radially-located in the case with 120-degree gap, and the forceps shaft is inserted among those rollers. When the outer case is rotated, the rollers travel on the surface of forceps spirally. The shaft is relatively driven by the driving rollers using friction force between rollers and surface of forceps in spiral trajectory. We adopted hollow-shaft ultrasonic actuators with optical encoder (rated torque 50mNm, custom order, Fukoku, Japan) because of various advantages of ultrasonic motor; compact size and light weight for miniaturization, high holding torque, clean environment for future clinical application, and suitable for hollow-shaft configuration. We use a couple of friction wheels with opposite tilting angle. They provide symmetrical spiral motions like right-handed and left-handed screws, and they are combined to generate rotation and translation (Fig. 4).

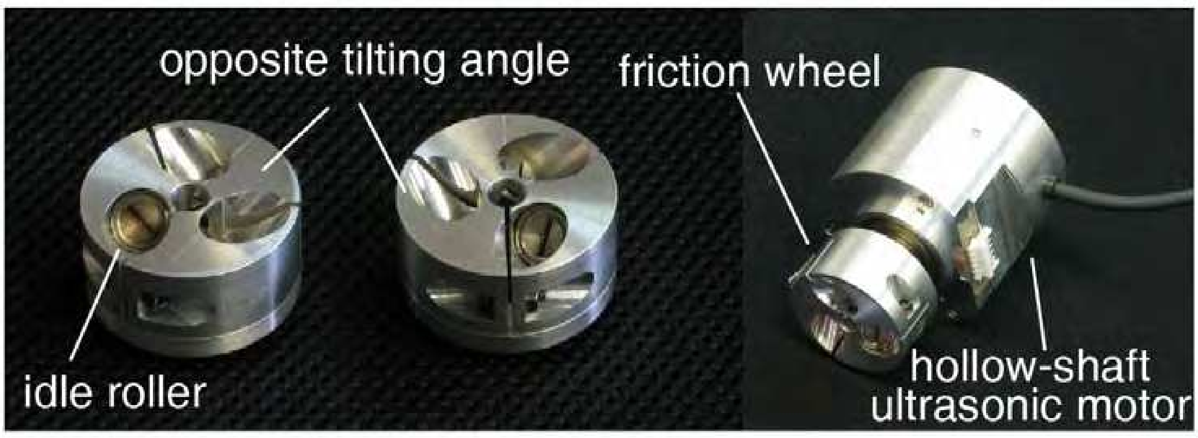

Figure 3. A couple of friction wheel; Each friction wheel has three tilted driving rollers with opposite tilting angle (left). Hollow-shaft ultrasonic motor is adopted for actuation (right)

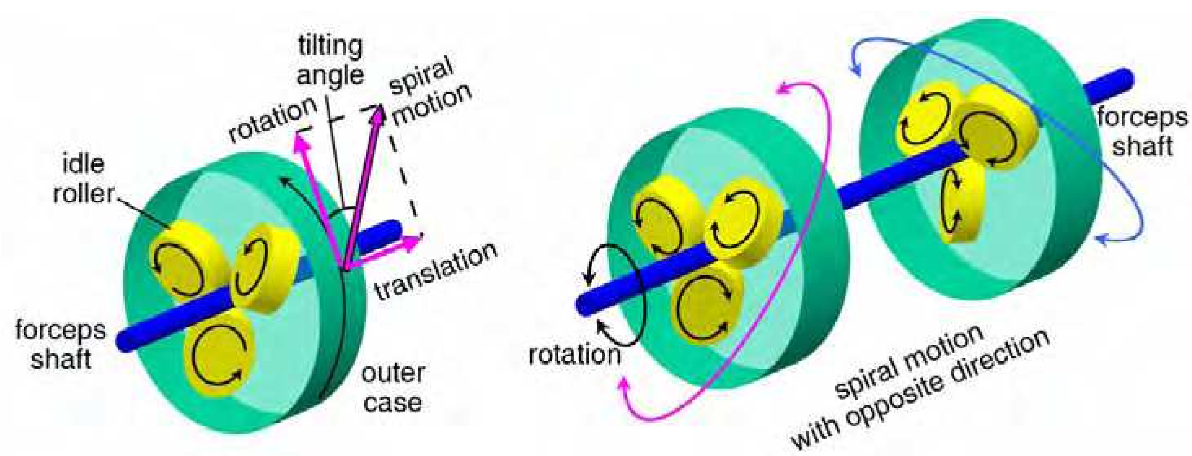

Figure 4. Friction wheel mechanism; friction wheel travels spirally around the forceps shaft (left). Opposite tilting angle generates two different spiral shapes like right-handed and left-handed screws (right)

For the axial rotation of forceps shaft, two friction wheels are rotated in the same direction. In that case, driving rollers and shaft does not have relative speed, so that spiral motions are not generated and forceps shaft rotates at the same speed of friction wheel. For the longitudinal translation, two friction wheels are rotated in the opposite direction. In this case, spiral motions are generated. The rotational components of spiral motion are cancelled mutually and remaining translation drives the forceps (Fig. 5).
The mechanism to generate translation can be shown using mathematical expression (Fig. 6).

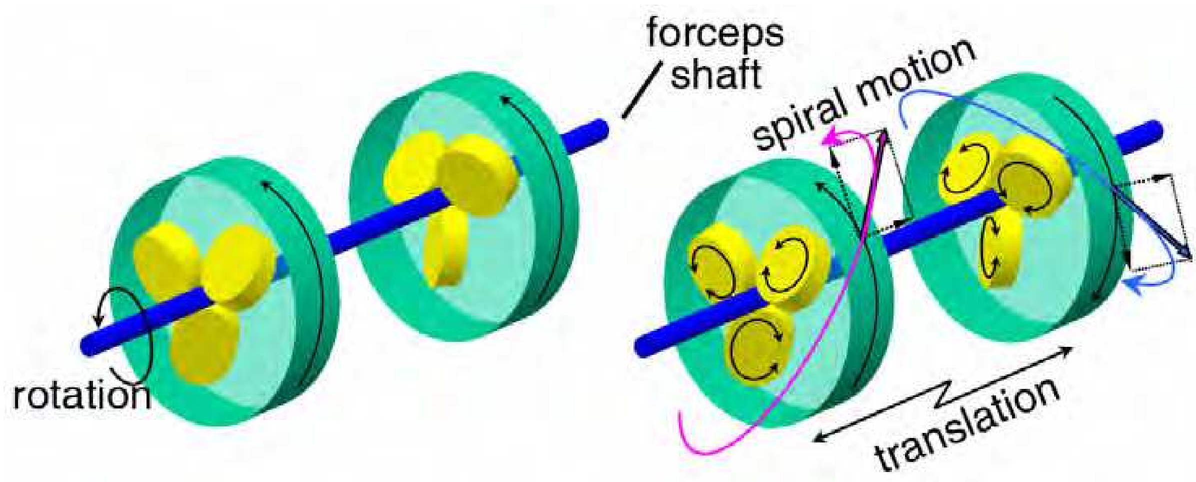

Figure 5. Driving principle of friction wheel mechanism: Rotational motion is generated by rotating both motors in the same direction (left). When each motor is driven in the opposite direction, rotational motions are cancelled mutually and remaining translational motion drives forceps in the longitudinal direction (right)

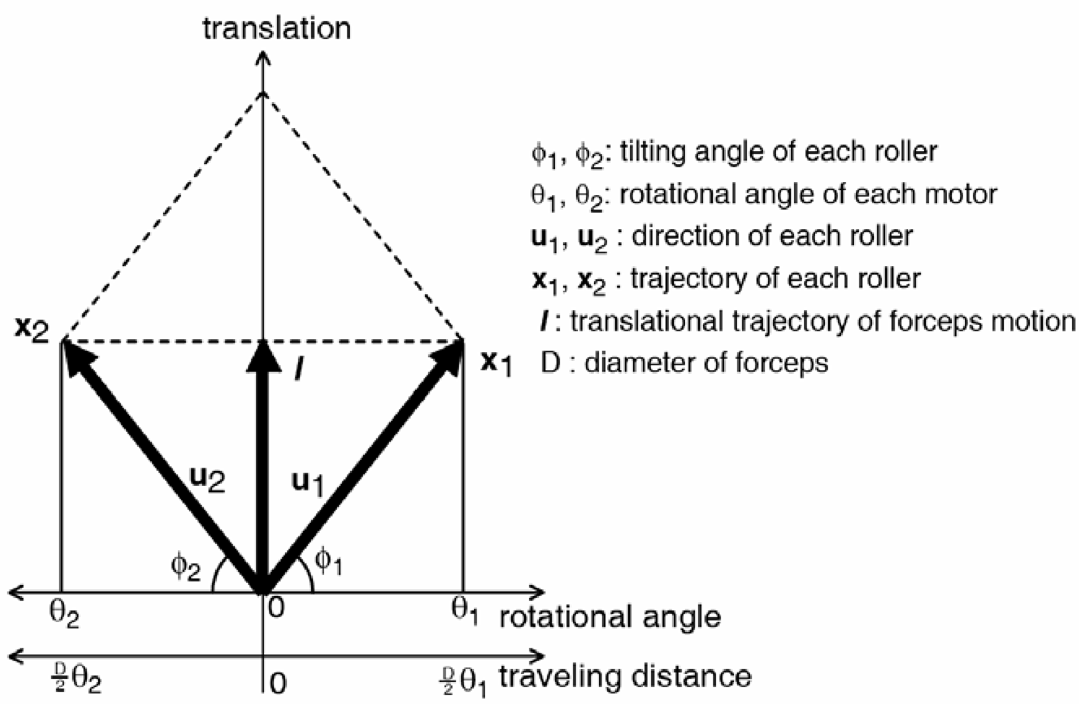

Figure 6. Translational motion can be shown by expanding the surface of forceps to a plane

Here, each roller has tilting angle of ϕ_1 and ϕ_2. When outer cases are rotated by θ_1 and θ_2, trajectory of each roller is as follows;

$$\begin{cases} x_1 = \dfrac{D}{2}\theta_1 u_1 = \dfrac{1}{2}\begin{bmatrix} D\theta_1 \\ D\theta_1 \tan(\phi_1) \end{bmatrix} \\ x_2 = \dfrac{D}{2}\theta_2 u_2 = \dfrac{1}{2}\begin{bmatrix} D\theta_2 \\ D\theta_2 \tan(\phi_2) \end{bmatrix} \end{cases} \quad (1)$$

As the traveling distance is written as the average of two friction wheels, translation can be express using rotational angle of each motor (θ_1 and θ_2) and tilting angle (ϕ_1 and ϕ_2);

$$
\begin{aligned}
l &= \frac{x_1 - x_2}{2} \\
&= \begin{bmatrix} \frac{D}{4}(\theta_1 - \theta_2) \\ \frac{D}{4}(\theta_1 \tan(\phi_1) + \theta_2 \tan(\phi_2)) \end{bmatrix} \\
&= \begin{bmatrix} \frac{D}{4}(\theta_1 - \theta_2) \\ \frac{D}{4}(\theta_1 + \theta_2)\tan(\frac{\pi}{6}) \end{bmatrix} \qquad \left(\phi_1 = \phi_2 = \frac{\pi}{6}\right) \\
&= \begin{bmatrix} 0 \\ \frac{D}{2}\theta \tan(\frac{\pi}{6}) \end{bmatrix} \qquad \left(\theta_1 = \theta_2 = \theta\right)
\end{aligned} \tag{2}
$$

Here, we used 30 deg ($\pi/6$ rad) for tilting angle of rollers and θ for rotational angle of each motor. As shown in eq. (2), the translational distance is controlled by the rotational angle of actuator like a ball screw.

This mechanism is proposed by Vollenweider for surgery simulator (Vollenweider, et al, 1998). Ikuta, et al. also adopted the similar mechanism for axial rotation and longitudinal translation of colonoscope in the virtual endoscope training system (Ikuta, et al., 1998). To the best of authors' knowledge, this is the first prototype that uses this kind of rotation and translation mechanism not for simulator but for real manipulator.

2.3 Gimbals mechanism

Gimbals mechanism has two mutually-perpendicular intersectional rotational axes and realizes pivoting motion of forceps with wide working range around the trocar port. The simple kinematics eases numerical control.

A concern about the location of rotational centre of the mechanism should be discussed. Many studies have proposed the necessity of the remote centre of motion (RCM) mechanism to realize pivot motion with no mechanical part at the trocar port; such as R-guide (Mitsuishi, et al., 2003) and parallel-linkage mechanism (Taylor, et al., 1995, Madhani, et al., 1998, and Kobayashi, et al., 2002). As gimbals mechanism has its rotational centre inside it, not at the incision hole, the rotational centre is located above trocar port and forceps pulls abdominal wall accompanying its pivot motion. As we reported in the past publication (Suzuki, et al., 2002), the result of preliminary in-vivo experiment using pig showed no problem; such as expansion of incision hole and bleeding. We conclude that gimbals mechanism will not damage the abdominal wall because abdominal muscle got relaxed under anaesthesia and incision hole follows the motion of forceps, although the required torque increased to pull the abdominal wall according to the pivot motion of forceps and actuators should be carefully selected. We adopted DC servomotor (ENC-185801, CITIZEN CHIBA PRECISION Co., LTD) to control each rotational axis.

3. Evaluation

3.1 Separation between translation and rotation

One of advantages of FWM is that it realizes rotation and translation with one miniaturized mechanism. For appropriate rotation and translation, we need two conditions; one is the shape of each spiral and the other is rotational speed of each motor. In other words, the lead length of each spiral motion generated by friction wheel should be the same, and rotational speed of each motor should be the same. This is because rotational component of spiral motion must be the same to be cancelled mutually. Our former studies, however, showed that the friction wheel mechanism provided rotational error in translation. We measured the rotational error when 90 mm translation, equivalent to 1800 deg rotation of actuator, was input. The rotating angle of each actuator was controlled using pulse signal from rotary encoders mounted on the motor. The rotating angle of forceps shaft was measured using digital microscope (VH-7000C, Keyence, Japan) with 0.5 deg resolution. The result of error evaluation is shown in Table. 1 (Suzuki, et al., 2005). Measured error was large compared to the required specification we set for this manipulator.

input	error factor	required spec.	average +/- S.D.
translation (90 mm, 1800 deg)	rotation	less than1 deg	14.5 +/- 3.0 deg

Table 1. Rotational error of friction wheel mechanism in translational input

3.2 Error analysis based on mechanical error

For the error correction, we analyze the cause of rotational error in translational motion. As mentioned above, the error motion is caused by different spiral shape generated by each friction roller and/or different rotating angle of each actuator. As we control the actuators using rotary encoders, we can omit the possibility of different rotating angle. Thus, the cause of unstable motion is mismatch of lead length between each friction roller. Lead length error is caused by tilting angle error of the friction rollers. The angle error is determined by the machining error in prototyping process.

We discussed the cause of rotational error in translation and its correction method based on the mechanism of friction wheel. Error analysis is shown here using Fig. 7.

Rotational error is shown as follows;

$$\Delta\theta = \frac{1}{2}(\hat{\theta}_1 - \hat{\theta}_2) \tag{3}$$

Because the forceps shaft is rigid, the translational distance generated by each roller is the same, and sum of rotational angle are the same between each roller.

$$\begin{cases} \hat{\theta}_1 \tan(\phi + \Delta\phi_1) & = & \hat{\theta}_2 \tan(\phi + \Delta\phi_2) \\ \hat{\theta}_1 + \hat{\theta}_2 & = & \theta_1 + \theta_2 \end{cases} \tag{4}$$

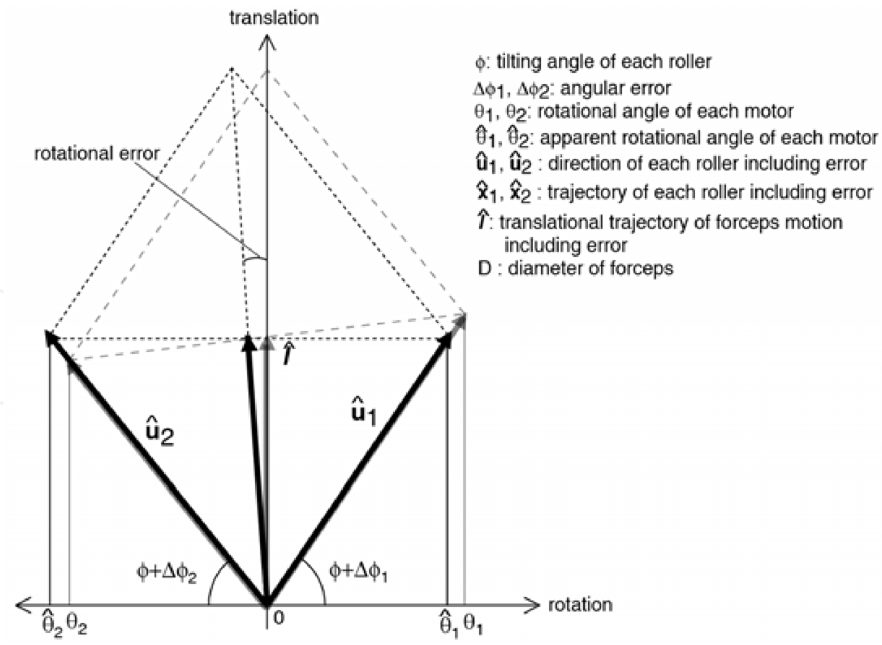

Figure 7. Error analysis of rotational error in translational motion

When these simultaneous equations (4) are solved for $\hat{\theta}_1$ and $\hat{\theta}_2$, they are shown as follows;

$$\begin{cases} \hat{\theta}_1 = \dfrac{\tan(\phi+\Delta\phi_2)}{\tan(\phi+\Delta\phi_1)+\tan(\phi+\Delta\phi_2)}(\theta_1+\theta_2) \\ \hat{\theta}_2 = \dfrac{\tan(\phi+\Delta\phi_1)}{\tan(\phi+\Delta\phi_1)+\tan(\phi+\Delta\phi_2)}(\theta_1+\theta_2) \end{cases} \tag{5}$$

Consequently, Δθ (eq. (3)) is shown using eq.(5).

$$\begin{aligned} \Delta\theta &= \frac{1}{2}(\hat{\theta}_1-\hat{\theta}_2) \\ &= -\frac{1}{2}\frac{\tan(\phi+\Delta\phi_1)-\tan(\phi+\Delta\phi_2)}{\tan(\phi+\Delta\phi_1)+\tan(\phi+\Delta\phi_2)}(\theta_1+\theta_2) \end{aligned} \tag{6}$$

This means that the rotational error is proportional to the sum of input rotating angle (θ_1, θ_2), and that the coefficient is determined using only mechanical error of tilting angle ($\Delta\phi_1$ and $\Delta\phi_2$), thus the error could be compensated using correction factor. On the assumption that rotational error of Δθ is observed when angle of θ_0 is input to generate translation, the correction factor is analyzed. As the condition, we have following equations. Equation (7) means the translational distance is expressed in two ways. The first equation in eq.(8) means input angle for each driving roller is the same in the case of translational input, and other equations are geometrically trivial.

$$\hat{\theta}_1\tan(\phi+\Delta\phi_1)=\frac{1}{2}\left(\theta_1\tan(\phi+\Delta\phi_1)+\theta_2\tan(\phi+\Delta\phi_2)\right) \tag{7}$$

$$\begin{cases} \theta_1 = \theta_2 & = \theta_0 \\ \tan(\phi + \Delta\phi_1) & = \dfrac{\hat{l}}{\hat{\theta}_1} \\ \tan(\phi + \Delta\phi_2) & = \dfrac{\hat{l}}{\hat{\theta}_2} \end{cases} \tag{8}$$

When equations (8) are assigned to eq.(6) and (7), $\hat{\theta}_1/\theta_0$ and $\hat{\theta}_2/\theta_0$ are shown as eq.(9).

$$\begin{cases} \dfrac{\hat{\theta}_1}{\theta_0} = \dfrac{-2k+1+\sqrt{4k^2+1}}{2} \\ \dfrac{\hat{\theta}_2}{\theta_0} = \dfrac{2k+1+\sqrt{4k^2+1}}{2} \\ \left(k = \Delta\theta/\theta_0\right) \end{cases} \Rightarrow \begin{cases} \dfrac{\hat{\theta}_1}{\theta_0} = 1-k \\ \dfrac{\hat{\theta}_2}{\theta_0} = 1+k \\ (k \ll 1) \end{cases} \tag{9}$$

As they are the error coefficient of driving rollers, the inverse of those coefficients are the correction factor C_1 and C_2 (eq.(10)).

$$\begin{cases} C_1 = \dfrac{\theta_0}{\hat{\theta}_1} = \dfrac{1}{1-k} = 1+k \\ C_2 = \dfrac{\theta_0}{\hat{\theta}_2} = \dfrac{1}{1+k} = 1-k \\ (k \ll 1) \end{cases} \tag{10}$$

Consequently, the correction factor can be expressed using k that is determined by input angle ($\Delta\theta$) and measured error angle (θ_0).

3.3 Re-evaluation of separation after compensation

We measured rotational error again. In this measurement, we applied the correction factor k by assigning 1800 deg to θ_0 and 14.5 deg to $\Delta\theta$. Result is shown in Table 2 comparing the result of the case without correction factor. The rotational error was reduced more than 90 % by the error correction factor (Suzuki, et al., 2005).

input	error factor	correction factor	average +/- S.D (deg)
translation (90 mm, 1800 deg)	rotation	without	14.5 +/- 3.0
		with	1.0 +/- 1.0

Table 2. Rotational error of friction wheel mechanism in translational input with/without correction factor

4. Discussion

For realization of stable forceps manipulation using friction wheel mechanism, we analyzed the mechanical configuration of manipulator and proposed a correcting factor based on the input rotating angle and measured rotational error, so that the error was reduced by 90%. When the 90 mm translation is input, the error was approximately 1.0 deg. In laparoscopic surgery, innermost target is sometimes located 300 mm from incision hole. In that case, the rotational error will increase up to approximately 3.0 deg. As it does not meet the required specification of 1deg accuracy, we have to find other causes of unstable motion.
One of possible causes is the variation of correction factor. We calculated the correction factor as a constant value from limited number of sets of measured error and input rotating angle. The error correction factor may change depending on the surface condition of forceps shaft, so we need to change correction factor dynamically. Another cause is slip between friction rollers and forceps shaft. In the current prototype, the forceps position is calculated from encoder value and controlled in semi-closed feedback loop. We do not consider position error caused by slight slip or its accompanying accumulated error.
These issues could be solved by closed feedback control loop using direct sensing of forceps position. As implementation methods, we can use three dimensional optical position sensor and/or texture recognition system like optical mouse.

5. Conclusion

In this study, we introduce a compact forceps manipulator with four DOFs for laparoscopic surgery. It consists of two mechanical parts; friction wheel mechanism and gimbals mechanism. Friction wheel mechanism is space-saving and realizes two degrees of freedom of rotation and translation using a couple of friction wheel. Gimbals mechanism realizes wide working range and easy control. One of the drawbacks of FWM, rotational motion error in translational input, was shown and analyzed mathematically based on the mechanical configuration of manipulator. Rotational error was reduced more than 90 % by the error correction factor calculated from the mathematical analysis of mechanical configuration.
In the future works, we will work to modify mechanical configuration based on the results of this study and improve control method from semi-closed feedback control using rotary encoders to closed feedback control using direct position sensing method, such as three-dimensional optical position sensor. As another future work, we will integrate this forceps manipulator with robotized forceps, such as laser coagulator forceps with CCD camera (Suzuki, et al., 2004).

6. Acknowledgement

This work is partly supported by following grants;
-“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)

-"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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Medical Robotics
Edited by Vanja Bozovic

ISBN 978-3-902613-18-9
Hard cover, 526 pages
Publisher I-Tech Education and Publishing
Published online 01, January, 2008
Published in print edition January, 2008

The first generation of surgical robots are already being installed in a number of operating rooms around the world. Robotics is being introduced to medicine because it allows for unprecedented control and precision of surgical instruments in minimally invasive procedures. So far, robots have been used to position an endoscope, perform gallbladder surgery and correct gastroesophogeal reflux and heartburn. The ultimate goal of the robotic surgery field is to design a robot that can be used to perform closed-chest, beating-heart surgery. The use of robotics in surgery will expand over the next decades without any doubt. Minimally Invasive Surgery (MIS) is a revolutionary approach in surgery. In MIS, the operation is performed with instruments and viewing equipment inserted into the body through small incisions created by the surgeon, in contrast to open surgery with large incisions. This minimizes surgical trauma and damage to healthy tissue, resulting in shorter patient recovery time. The aim of this book is to provide an overview of the state-of-art, to present new ideas, original results and practical experiences in this expanding area. Nevertheless, many chapters in the book concern advanced research on this growing area. The book provides critical analysis of clinical trials, assessment of the benefits and risks of the application of these technologies. This book is certainly a small sample of the research activity on Medical Robotics going on around the globe as you read it, but it surely covers a good deal of what has been done in the field recently, and as such it works as a valuable source for researchers interested in the involved subjects, whether they are currently “medical roboticists” or not.

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