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Development of a New Bending Mechanism and Its Application to Robotic Forceps Manipulator

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Abstract—**This paper proposes a new bending mechanism with a screw drive mechanism, which enables omni-directional bending motion by rotating two linkages consisted of right-handed screw, universal joint and left-handed screw. We call this mechanism double-screw-drive (DSD) mechanism. DSD mechanism was applied to a robotic forceps manipulator for laparoscopic surgery. In the first prototype, by adding the third linkage to DSD mechanism and rotating this, opening and closing motions of a gripper was attained. In the second prototype, DSD forceps manipulator was enhanced so that its gripper can rotate. This is achieved by rotating the third linkage in DSD mechanism. On the other hand, the opening and closing motions of a gripper is attained by wire-drive. The developed DSD forceps manipulator realizes bending motion without using wires. Therefore, it has high rigidity, and it can bend 90 degrees in arbitrary direction. In order to control the developed DSD robotic forceps manipulator as teleoperation system, joy-stick type manipulator for remote control was built and servo system was constructed for each linkage. Servo experiments show the effectiveness of the constructed control system.**

I. Introduction

Minimally invasive surgery has an excellent characteristic that can reduce a burden of patients. However, it causes difficult operation for surgeons due to the inflexibility of surgical instruments and small work space. Therefore, the development of surgical support devices with the application of robot technology is in demand [1]-[3]. In particular, the development of multi-DOF robotic forceps manipulators so as to realize complex human finger action in laparoscopic surgery is one of the most important subjects.

Many of conventional multi-DOF robotic forceps manipulators currently available for minimally invasive surgery are of wire-driven type [4],[5]. However, rigidity and durability of the wire are poor. Furthermore, sterilization capability against the wire is low.

In order to improve the sterilization capability and rigidity, multi-DOF robotic forceps manipulators that use the methods other than wire-driven for bending motion have been developed. These are roughly divided into two types. The one is the type where two degrees of freedom bending is achieved by combining independent joints that bend to horizontal direction and vertical direction respectively. The other one is the type which achieves omni-directional two degrees of freedom bending by inclination of the entire unit of bending part of forceps. As a one of the independent joints type forceps manipulators, an endoscopic forceps manipulator using a multi-slider linkage mechanism was developed in [6], in which the wire is used for gripping motion though it is not used for bending motion.

On the other hand, as a one of the omni-directional bending type forceps manipulators, a tripodal platform active forceps manipulator was developed in [7]. Though it has a high rigidity, its bending range is 40 or 50 degrees, and it is difficult to expand the bending range due to a constraint in mechanism.

This paper proposes a novel omni-directional bending mechanism with a screw drive mechanism that we call double-screw-drive (DSD) mechanism. DSD mechanism has two linkages consisted of right-handed screw, universal joint and left-handed screw. Usually, screw drive mechanism is used for translating motion, however in DSD mechanism, bending motion is occurred due to the existence of universal joint, and the rotation of two linkages enables omni-directional bending motion.

Furthermore, the DSD mechanism was applied to a multi-DOF robotic forceps manipulator. In the first prototype, by adding the third linkage to DSD mechanism and rotating this, opening and closing motions of a gripper is attained. Therefore, both bending motion and gripping motion of a gripper are achieved without using wires. The built robotic forceps manipulator has high rigidity, large bending range of 90 degrees in any direction, and small drive unit as compared with the conventional multi-DOF robotic forceps manipulators currently used in minimally invasive surgery.

On the other hand, in order to do a suture work in small work space such as the other side of internal organs, roll motion of a gripper is indispensable. A miniaturized rotary gripper with wire-driven was developed in [8]. Therefore, in the second prototype, the proposed DSD forceps manipulator was modified so that its gripper can rotate to achieve enhanced maneuverability in laparoscopic surgery. This is achieved by rotating the third linkage in DSD mechanism, while the opening and closing motions of a gripper is attained by wire-drive. Furthermore, to facilitate assembly and disassembly of the DSD forceps manipulator, number of the parts in bending part was reduced in the second prototype. Moreover, total length of the bending part was shortened compared with the first prototype. As a result, back-lash

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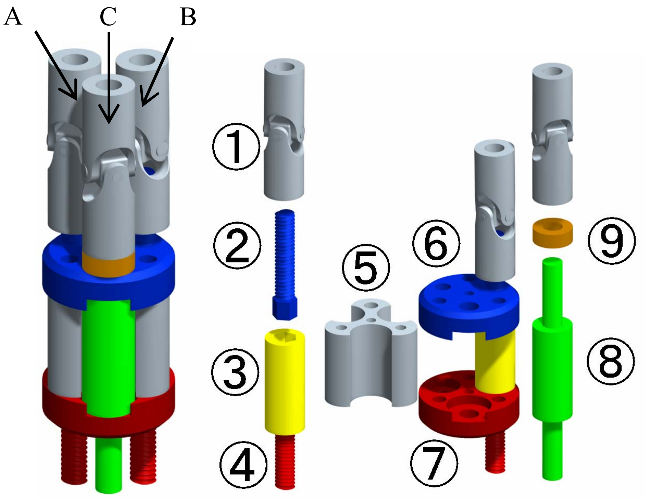
occurred in the bending part was also reduced.

In order to control the developed DSD robotic forceps manipulator as teleoperation system, joy-stick type manipulator for remote control is also built and servo system was constructed for each linkage. Bending motion experiments show the effectiveness of the constructed control system.

II. Structure of Bending Mechanism

One block of bending mechanism shown in Figure 1 consists of nine kinds of parts. Hereafter, we call this mechanism as double-screw-drive (DSD) mechanism throughout this paper.



A and B: Bending linkage, C: Grasping linkage

1. Universal joint
2. Right-handed hex-head cap screw
3. Spline with hex-head hole
4. Left-handed hex-head cap screw
5. Spline bearing
6. Plate with right-handed screw hole
7. Plate with left-handed screw hole
8. Spline shaft
9. Washer

Fig.1 One block of DSD mechanism

DSD mechanism has three linkages which are assigned on the circumference of a circle with diameter 6[mm] by center angle of every 120 [degrees]. Let say a group of universal joint, right-handed hex-head cap screw, spline with hex-head hole, and left-handed hex-head cap screw as "bending linkage" and a group of universal joint, washer and spline shaft as a "grasping linkage". The omni-directional bending motion is achieved by rotating two bending linkages, and grasping linkage can be used for another purpose.

The rotation power imposed to the bending linkage is transmitted to left-handed hex-head cap screw, spline with hex-head hole, right-handed hex-head cap screw, and universal joint in turn. Then, the spline has a penetration hole of hex-head shape so that the hex-head cap screw can transmit the rotation power to the spline with translating inside of the spline. That is, left-handed hex-head cap screw, plate with left-handed screw hole, spline, plate with right-handed screw hole, and right-handed hex-head cap screw take a role of turnbuckle.

When another block of DSD mechanism is connected after one block, a joint is formed. Principle of the bending motion for one joint is illustrated in figure 2.

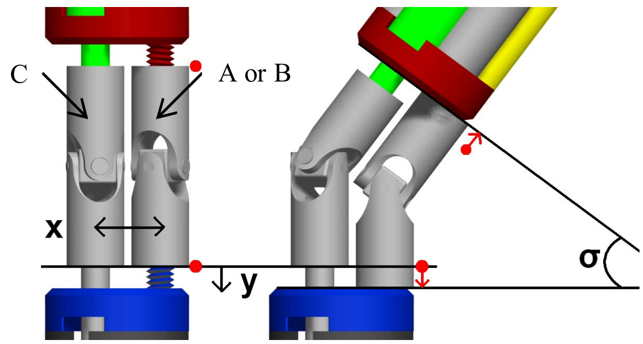


Fig.2 Principle of bending motion

The left-handed hex-head cap screw connects with the plate with left-handed screw hole, and the right-handed hex-head cap screw connects with the plate with right-handed screw hole. Also, the right-handed hex-head cap screw and the left-handed hex-head cap screw are fixed on the universal joint by stop screws. The rotation of the linkage changes connecting length of screw and plate at both ends of universal joint. As a result, an inclination is occurred between the plates at both ends. For example, when the linkage rotates clockwise, the plates at both ends approach each other and when the linkage rotates counter clockwise, the plates at both ends part from each other. Thus, bending motion is achieved. The maximum bending angle of one joint is 30 [degrees], since it is the allowable bending angle of the universal joint.

One bending linkage enables bending motion in one direction, and using two bending linkages and controlling the amount of revolutions of them, arbitrary omni-directional bending motion is attained.

III. DSD Forceps Manipulator

A. Specifications

The important specifications of multi-DOF robotic forceps manipulators are given as follows [6].

1. Diameter of a forceps must be less than 10[mm], which enables to insert the forceps into a trocar.
2. Bending power more than 4[N] is necessary, which enables the forceps to lift up 1/3 of liver.
3. At least bending range must be from -90 to 90 [degrees] in horizontal and vertical direction, respectively.

B. Application to Robotic Forceps Manipulator

The proposed DSD mechanism is applied to a multi-DOF robotic forceps manipulator. Figure 3 shows a whole configuration of DSD forceps manipulator.

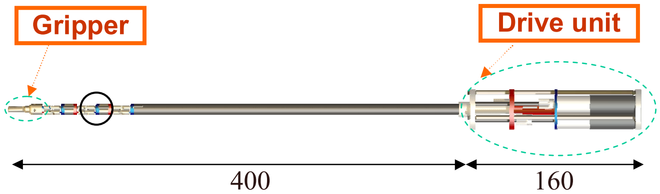


Fig.3 DSD forceps manipulator

The portion that enclosed a circle in Figure 3 is one block of the DSD mechanism illustrated in Figure 1. Since the maximum allowable bending angle of one joint is 30 [degrees], the bending part of DSD forceps manipulator consists of three blocks of DSD mechanism to bend ±90 [degrees], whose total length is 85[mm] excluding a gripper. While, total length of the DSD forceps manipulator is 560[mm].

Each motor shaft in drive unit and each linkage in bending part are connected by rod of 2[mm] in diameter and 300[mm] in length. The rotation power from the motor is transmitted to each linkage through the rod. Then, the driving power imposed to the bottom block in bending part is transmitted toward the top block one after the other due to the principle of DSD mechanism illustrated in Section II.

C. Gripper

In the first prototype, the opening and closing motions of a gripper is achieved by rotating grasping linkage.

A screw is not processed on the spline shaft in grasping linkage, and both ends of the spline shaft are fixed on the universal joint by stop screws. Therefore, grasping linkage can only bend passively and rotation power is transmitted to the top of the grasping linkage. The screw is processed on the tip of the grasping linkage, and center shaft of the gripper is translated by screw drive. This is achieved by rotating the grasping linkage. Then, tip of the center shaft of the gripper slides in the slit of holding parts of the gripper. As a result, opening and closing motions of the gripper is attained. As for the holding parts and center shaft, same mechanism of currently existing forceps is adopted. The closing and opening states of the gripper are shown in Figure 4.

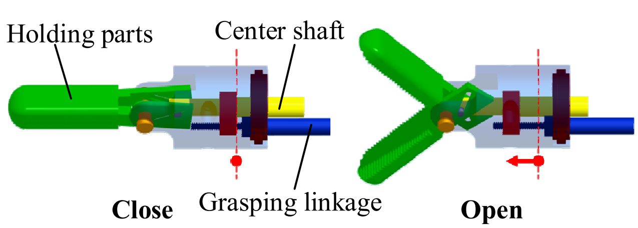


Fig.4 Gripper

D. The First Prototype

The first prototype DSD forceps manipulator is shown in figure 5, whose total length is 120[mm] including the gripper.

Fig.5 The first prototype DSD forceps manipulator

IV. Kinematics of DSD Forceps Manipulator

A. Constraint in Mechanism

As shown in Figure 2, when looking at one joint of the DSD mechanism from side view of bending direction of the forceps, let a farthest distance between linkages in horizontal direction be x, and let a distance where the screw translated vertically against the plate be y. Then, the relative bending angle between the plates at both ends of universal joint σ is given as follows.

$$\sigma = 2\tan^{-1}\frac{y}{x} \qquad (1)$$

Since the bending part consists of three blocks of DSD mechanism, the whole bending angle θ of DSD forceps manipulator is given by

$$\theta = 3\sigma \qquad (2)$$

When looking at the DSD mechanism from top view, the length of one of the sides of equilateral triangle formed by these three linkages is 5.2[mm], and the distance from the top of the equilateral triangle to the facing side is 4.5[mm].

Substituting the maximum bending angle for one joint $\sigma_{\max}$ =30 [degrees] and $x_{\max}$ =5.2[mm] to the equation (1), $y_{\max}$ =1.4[mm] is obtained. Thus, when each screw translates 1.4[mm] vertically against each plate, the bending angle of the DSD forceps manipulator becomes 90 [degrees]. This corresponds to 3.5 revolutions of the bending linkage in the case where an average M2 screw of pitch 0.4[mm] is used.

As for the opening and closing motions of the gripper, when the grasping linkage gets 7 revolutions, the gripper opens to the maximum from closed state.

B. Inverse Kinematics

Consider such an inverse kinematics problem that determines amount of revolutions for the two bending linkages so as to realize an arbitrary bending state based on the elevation and the azimuth of the forceps manipulator.

The coordinates for the forceps manipulator are shown in Figure 6, where θ represents the elevation which is the deflection of the forceps from the vertical, and ϕ represents the azimuth which is the angle between the forceps and the grasping linkage. We call θ as "bending angle" and ϕ as "rotation angle", respectively.

Let a pitch of screw represent p, and let a maximum translated distance of the screw as the bending angle being θ represent $y_{\theta\max}$. Then, the maximum amount of revolutions of the bending linkage δ to realize an arbitrary bending angle θ is expressed as follows.

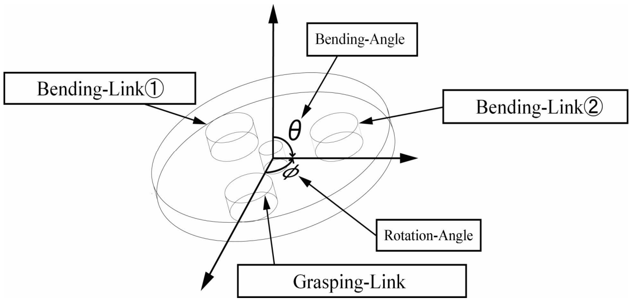


Fig.6 Bending-Rotation coordinates

$$\delta = \frac{y_{\theta \max}}{p} \tag{3}$$

From the equation (2), in the case where three blocks of DSD mechanism is used, $y_{\theta\max}$ is given by

$$y_{\theta \max} = x_{\max} \tan\frac{\sigma}{2} = 5.2\tan\frac{\theta}{6} \; . \tag{4}$$

Then, the amounts of revolutions of the bending linkage A denoting α and linkage B denoting β are given respectively as follows.

$$\alpha = \delta\cos(\phi - 30°) \tag{5}$$

$$\beta = \delta\cos(\phi + 30°) \tag{6}$$

Thus, provided the bending angle θ and the rotation angle ϕ, the amounts of the revolutions of each linkage α and β are obtained.

V. Bending and Grasping Experiments

A. Manipulator for Remote Control

In a laparoscopic surgery, multi-DOF robotic forceps manipulators are operated by remote control. In order to control the proposed DSD forceps manipulator as teleoperation system, joy-stick type manipulator for remote control was also designed and built by reconstruction of a ready-made joy-stick, in which the shaft of the ready-made joy-stick is removed, and a general forceps without bending mechanism used in conventional laparoscopic surgery, so called straight forceps, is inserted instead. Furthermore, linear encoder was installed in the straight forceps in order to detect a transferred distance of the grasping part of the straight forceps. Therefore, the built joy-stick type manipulator enables to control the bending and gripping motions of the proposed DSD forceps manipulator. Configuration of the built joy-stick type manipulator is shown in Figure 7.

B. Control System

The bending angle θ and the rotation angle ϕ of the joy-stick are measured by potentiometers installed in joy-stick. Then, amount of revolutions of the bending linkages α and β are calculated through the inverse kinematics. Also, the transferred distance d of grasping part of the joy-stick forceps is measured by linear encoder. Then, amount of revolutions of the grasping linkage γ is obtained through calculations. These values are referred as reference inputs, and servo systems are constructed so that the actual amount of revolutions of the linkages can track the reference inputs.

Fig.7 Joy-stick type manipulator for remote control

DC micro motors 1727U012C (3.65W) produced by FAULHABER Corp. are used for three motors in drive unit. Rotary encoder and deceleration gear are installed in each motor. The block diagram of the control system is shown in Figure 8. For the simplification, PI controller is applied to the servo system under the Matlab/Simulink software environment. Controller gains of PI controller were adjusted by trial and error through repetition of experiments.

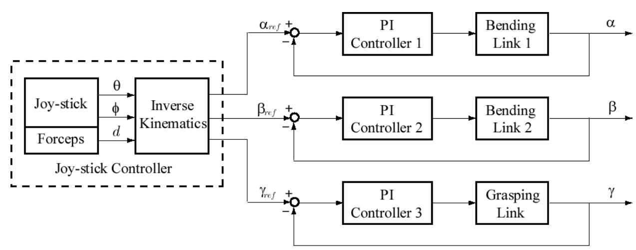


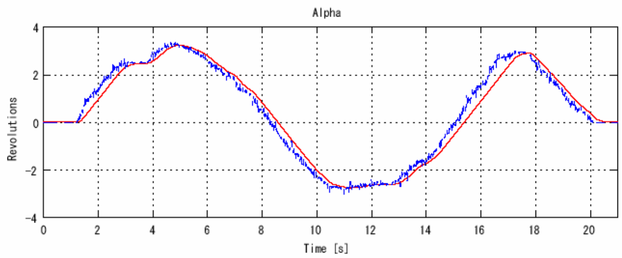
Fig.8 Control block diagram

C. Servo Experiments

Using the control system described in Figure 8, such servo experiments that the inclination of the bending part of DSD forceps tracks the inclination of the joy-stick forceps, and the opening and closing motions of the gripper of DSD forceps tracks the opening and closing motions of the grasping part of the joy-stick forceps were executed.

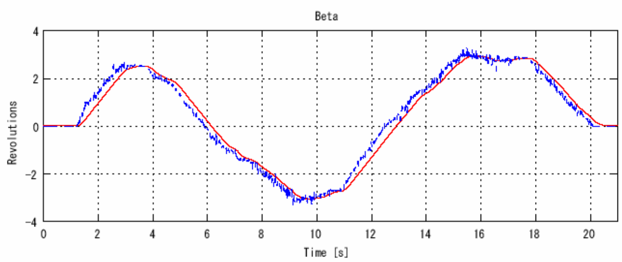
In the bending motion, bending angle of the joy-stick forceps was inclined to the maximum and rotation angle of the joy-stick forceps was rounded so that the tip of DSD forceps draws circular orbit. In the opening and closing motions, the grasping part of the joy-stick forceps was firstly opened from closed state and once it reached to the maximum, it was closed again so that the gripper of DSD forceps performs opening and closing motions.

The experimental results are shown in Figure 9 to Figure 11, where broken line shows reference value and solid line shows actual amount of revolutions of the linkage. From the experimental results, it can be seen that the amount of revolutions in each linkage tracks the reference value well. In practice, the tip of DSD forceps drew smooth circular orbit with tracking the motion of joy-stick forceps, and opening and closing motions of the gripper of DSD forceps was realized.



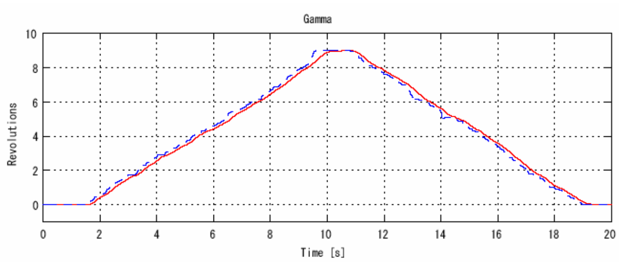
----: α_{ref} —: α

Fig.9 Experimental results for bending linkage A



----: β_{ref} —: β

Fig.10 Experimental results for bending linkage B



----: γ_{ref} —: γ

Fig.11 Experimental results for grasping linkage C

D. Bending Strength Experiment

Bending strength experiment was carried out using the proposed DSD forceps manipulator. A pet bottle of weight of 500[g] filled with water was hung on a tip of the forceps. Then, the forceps was forced to bend up to 90 [degrees]. As a result, it turned out that the bending power of 4[N] is satisfied.

E. Considerations

However, there exists about 8 [degrees] of back-lash in the bending part of the first prototype DSD forceps manipulator. This is caused by an accumulation of clearances of the universal joint and screw part of the bending linkage. Since clearance is necessary to guarantee allowable bending range of the universal joint, we consider to reduce the back-lash by shortening the total length of bending part in the next prototype. Furthermore, assembly and disassembly of the first DSD forceps manipulator were complicated due to a large number of the component parts in bending part. Therefore, we also consider to reduce the number of the parts in bending part.

VI. Improvement of DSD Forceps Manipulator

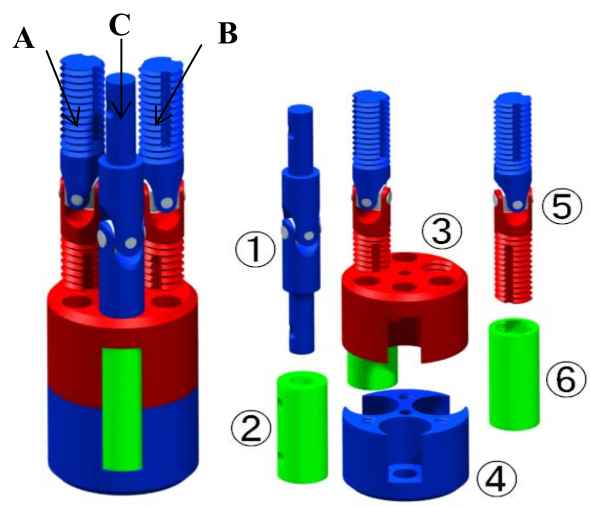
A. Main Improved Points

The main improved points in the second prototype DSD forceps manipulator are summarized as follows.

1) In order to do a suture work in small work space such as the other side of internal organs, roll motion of gripper is indispensable. Therefore, the proposed DSD forceps manipulator was modified so that its gripper can rotate to achieve enhanced maneuverability in laparoscopic surgery. This is achieved by rotating the grasping linkage in DSD mechanism, while the opening and closing motions of a gripper is attained by wire-drive.
2) The total length of the bending part was shortened compared with the first prototype. As a result, back-lash occurred in the bending part was reduced.
3) To facilitate assembly and disassembly of the DSD forceps manipulator, number of the parts in bending part was reduced.

B. Bending Mechanism

One block of the improved DSD mechanism is shown in Figure 12, which consists of six kinds of parts.



A and B: Bending linkage, C: Grasping linkage

1. Universal joint shaft
2. Coupling
3. Plate with left-handed screw hole
4. Plate with right-handed screw hole
5. Screwed universal joint
6. Spline with bumped hole

Fig. 12 One block of improved DSD mechanism

Principle of the bending motion is same as the first prototype DSD forceps manipulator. However, as compared with the first prototype which consisted of 15 parts per one block, the second prototype DSD forceps manipulator consists of 8 parts per one block. That is, 7 parts were reduced. For example, three parts in the first prototype, right-handed hex-head cap screw, universal joint and left-handed hex-head cap screw, are united to one part called screwed universal joint in the second prototype. This makes it easy to assemble and disassemble the DSD forceps manipulator. Then, one side of the screwed universal joint is left-handed screw and the other side is right-handed screw, which also have such grooves that can accord with the shape of bumped penetration hole of the spline. Thus, the screwed universal joint can transmit the rotation power to the spline with translating inside of the spline.

At the same time, the length of one block was 7[mm] shortened. The bending part of DSD forceps manipulator consists of three blocks of DSD mechanism, which means that total length of the bending part was 21[mm] shortened. Therefore, 8 [degrees] of back-lash occurred in the first prototype DSD forceps manipulator was also reduced to about 4 [degrees]. In order to reduce the back-lash more, it is necessary to miniaturize a universal joint itself. The total length of the bending part is 59[mm] excluding a gripper.

C. Rotary Gripper

In the second prototype DSD forceps manipulator, the grasping linkage is used for rotation of a gripper instead of opening and closing motions of a gripper. Mechanism of the rotary gripper is illustrated in Figure 13. The gear1 on the tip of the grasping linkage and the gear2 in the root of holding parts bite each other, and the holding parts are turned by rotation of the grasping linkage.

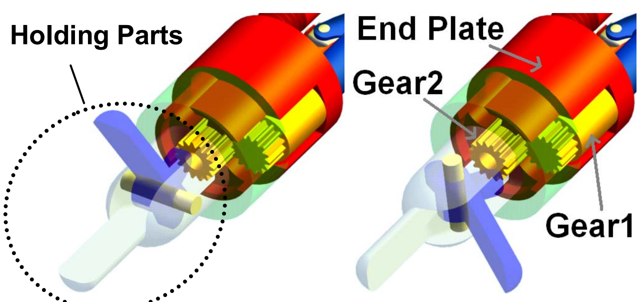


Fig.13 Rotation of hand unit

D. Opening and Closing of Holding Parts

The opening and closing motions of the gripper is wire-drive. Only one side of the holding parts can move. The other side of the holding parts is fixed. The wire for the drive goes through inside of the forceps and is pulled through friction pulley. The closing and opening states of the gripper are shown in Figure 14.

E. The Second Prototype

The second prototype DSD forceps manipulator is shown in figure 15, whose total length is 85[mm] including the gripper.


Fig.15 The second prototype DSD forceps manipulator

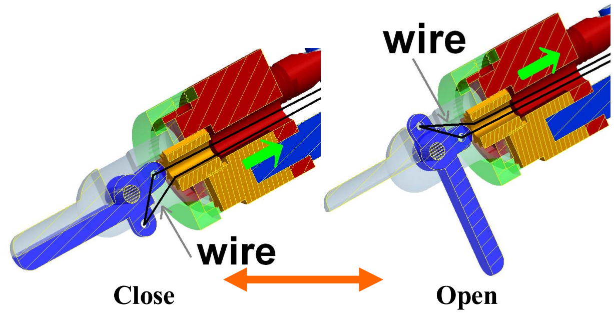


Fig.14 Gripper

VII. Conclusion

In this paper, a novel bending mechanism, so called double-screw-drive (DSD) mechanism was proposed, and DSD mechanism was applied to a multi-DOF robotic forceps manipulator for laparoscopic surgery. In order to control the proposed DSD forceps manipulator as teleoperation system, joy-stick type manipulator for remote control was also built and tracking control experiments were carried out to verify the bending motion of the DSD forceps manipulator. Experimental results showed the effectiveness of the constructed servo system.

Furthermore, the first prototype DSD forceps manipulator was modified so that its gripper can rotate to achieve enhanced maneuverability in laparoscopic surgery.

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