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Development of a 6-DOF Manipulator Driven by Flexible Shaft for Minimally Invasive Surgical Application

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***Abstract*— this paper presents a 6-DOF manipulator which consists of four parts, 1-DOF translational joint, two 2-DOF bending joints (segment1 and segment2), and 1-DOF rotational gripper. The manipulator with "flexible shaft and Double Screw Drive (DSD) mechanism" structure can obtain omni-directional bending motion through rotation of flexible shafts. In the first prototype, the flexible shafts were connected directly with the actuators in the manipulator. Compared with the first prototype, in the second prototype, flexible shafts for power transmission are connected to the base of the manipulator. Universal joints are used for power transmission to realize distal motion. The improvement done with the design of the second prototype reduced the torque necessary to drive the flexible shafts during motion in surgical interventions. Experiment results show that the manipulator has enough range of movement for surgical intervention.**

I. INTRODUCTION

Minimally Invasive Surgeries (MIS) have cosmetic advantages and reduce patient's burden [1]. However, laparoscopic surgery introduces new difficult operations for surgeons due to inflexible instruments and small workspace. Multi-DOF manipulators can realize complex movements in confined workspace, where the human's hand is hard to approach.

In order to improve the operability in small workspaces, forceps manipulators should be designed with small size and high rigidity. Thus, power transmission of manipulator is an important factor for manipulator design. *EndoWrist* manipulator, designed by Intuitive Surgical Inc., uses wires as actuators [2]. However, rigidity and durability of the wire is a critical flaw, furthermore, preload of wire-driven structure make installation become very complex. Nabil Simaan *et al.* presented a snake-like device with high elasticity central backbone tube. The device has omni-directional bending motion by pushing and pulling the tubes [3-4]. Dupont *et al.* developed an approach toward construction of robot with a concentric combination of pre-curved elastic tubes. Rotation and extension of the tubes control the robot's attitude [5]. Although tube-driven manipulators can attain dexterity, they bend easily under radial loads.

Ishii *et al.* presented a new robotic forceps manipulator with a novel Double-Screw-Drive (DSD) mechanism. The forceps manipulator consisted of three segments that can bend *30 degrees* each, with a total bending angle of *90 degrees* [6]. Their proposed manipulator can provide high rigidity with small diameter, but the three segments could not bend respectively, what reduces its dexterity in confined workspace. Kobayashi *et al.* presented an alternative SPS robot with DSD mechanism [7], limited by the one segment for bending motion, the manipulator was difficult for dexterous operation.

In this paper, we propose an omni-directional bending manipulator with DSD mechanism for surgical application. High rigidity is achieved to sustain axial and radial load. The flexible shaft are used for power transmission, which can bend easily, thus, being able to pass through irregular paths, but have high radial stiffness for torque transmission.

Two prototypes are presented in this paper. In the first prototype, every motion unit is connected directly to an actuator with a flexible shaft, which can achieve high rigidity and easy assembly, but, this manner will increase the motor's load due to the flexible shaft bending in a small radius arc. In the second prototype, the connection between flexible shaft and actuator has been modified. Several universal joints were used to transmit power from the base to the distal joint. With the new design, the bending joints of the manipulator can easily bend *90 degrees* in any direction.

II. DESIGN OF THE 6-DOF MANIPULATOR

A. Overview

The main structure of manipulator consists of four parts, translational joint (1-DOF joint for axial movement), two bending joints (4-DOF joints for omni-directional bending motion) and a rotational gripper (1-DOF rotation joint and a forceps), that can be replaced by other tool, such as cautery. Due to the required small incisions in the SPS, the diameter of the designed manipulator is *8mm*. The total length of the manipulator is *75.8 mm*. The main structure of manipulator is shown in Fig.1.

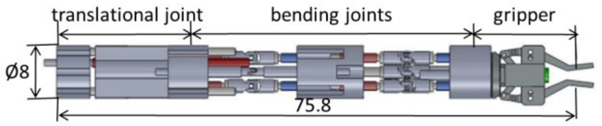

Figure 1. The overview of main structure of manipulator

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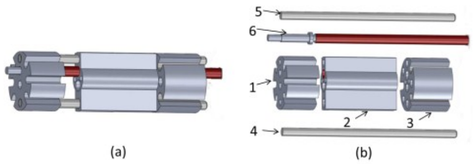


(a). assembled state, (b). exploded state. 1. base, 2.guiding block, 3.general plate for bending segment, 4,5.guiding rod, 6.screwed rod

Figure 2. Mechanism of translational joint

B. *Translational joint*

Fig.2 shows the 1-DOF translational joint mechanism.

The translational joint consists of six parts, a general plate (3) will move linearly when the screwed rod (6) rotates. The translational range is *20 mm*. In order to keep high rigidity, a guiding block (2) was introduced.

C. *Bending joints*

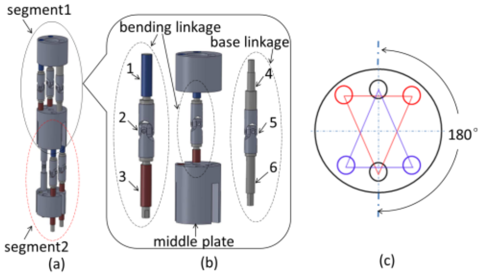
The manipulator is designed for surgical application. Therefore, it must be able to realize surgical operations such as suturing, that requires high dexterity.

We define the group of a left-handed screw, a right-handed screw and a universal joint as “bending linkage”, the group of a universal joint, a support rod as “base linkage”. Fig.3 shows the bending mechanism. It consists of two segments (segment1 and segment2), each segment includes two bending linkages and one base linkage, operation of any of the two bending linkages will create an omni-directional bending motion.

In the bending mechanism, two segments stucture was adopted, which can realize a big bending angle. Segment1 and segment2 can be controlled respectively, which improves the operational dexterity during surgery. In order to transmit rotation between segment1 and segment2, the distribution of linkages on the middle disk is shown in Fig.3(c). The angle of distribution between linkages in segment1 and segment2 is *180°*, the distribution of base linkages can provide high rigidity for surgical intervention.

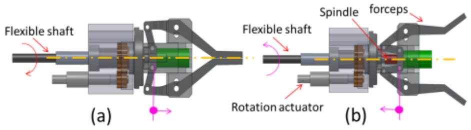
D. *Rotational gripper*

On surgery, the gripper should assist surgeon for tissue grasping and suture operation, the gripper must adjust the posture for proper surgical intervention. In our proposal, a gripper with 1-DOF rotation, opening and closing forceps was designed. The gripper is shown in Fig.4.



1.left-handed screw, 3.right-handed screw, 2,5.universal joint, 4.the upper support rod, 6. the lower support rod (a) two segments for bending motion, (b) explored structure of segment1, (c) distribution of rods on the middle plate

Figure 3. Mechanism of bending joints



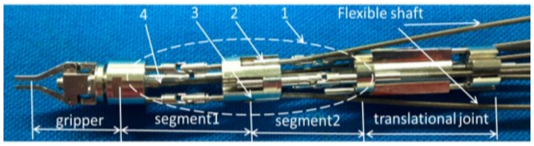
(a). close state, (b). open state

Figure 4. Mechanism of gripper

The gripper consists of a rotation part and a forceps. Rotation actuator rotates along its axial line. Meanwhile, the forceps will rotate along spindle’s axial line. A flexible shaft is connected to the gripper actuator, the rotation of the flexible shaft will be transmitted to the spindle, that drives the tip to open or close the forceps.

E. *The first prototype of manipulator*

Fig.5 shows the first prototype of the manipulator. The flexible shaft pass through segment2 directly to connect to the actuators of segment1.



1. bending joints. 2,3. connector between flexible shaft and DSD bending linkages. 4. connector between flexible shaft and forceps

Figure 5. The first prototype of manipulator

III. KINEMATICS OF MANIPULATOR

The manipulator consists of four parts, according to change the length of rods in the bending linkage, the omni-directional bending motion can be attained. The manipulator should have a bending range from *-90 degrees* to *90 degrees* at least, it can provide high dexterity on surgery.

A. *Instantaneous kinematics of manipulator*

In the designed manipulator, the length of base linkages are constant, based on base linkages, the coordinate system of manipulator is presented in Fig.6.

The necessary geometry of manipulator is shown in Fig.6(a), the distribution of DSD mechansim is shown in Fig.6(b), rod *AM*, *MA’*, *DN*, *ND’* are rods in the base linkages, each segment can realize two directional bending motion.

Define manipulator in its straight configuration as the initial state. $d_0=22mm$, $d_1=6.7mm$, $d_2=6.7mm$, $d_3=10mm$, $d_4=6.7mm$, $d_5=6.7mm$, $d_6=6mm$, $d_7=11mm$.

Since, the distribution of linkages in segment1 and segment2 are identical, the relation of rods’ length and bending angle of segment1 is discussed in Fig. 6(c). H_1, H_2 - the length of active rods in the bending linkages. The relation of rod’s length and bending angle are given by,

$$\begin{aligned} H_1 &= (2L_1 \cdot tg\theta_4 + 2d_4 + L_2 \cdot tg\theta_5)/2 \\ H_2 &= (2L_1 \cdot tg\theta_4 + 2d_4 - L_2 \cdot tg\theta_5)/2 \end{aligned} \qquad (1)$$

where, *L_1- the distance between base linkage and bending linkage*

L_2- the distance between two bending linkages on the middle disk

While θ_4 and θ_5 satisfy conditions of $\theta_4 = 0°$, $\theta_5 = \pm$

45° or $\theta_4 = \pm 45^{\circ}$, $\theta_5 = 0^{\circ}$,based on (1), length of active rods can be calculated as, $H_{1\_max} = 8.56mm$, $H_{1\_min} = 4.84mm$.

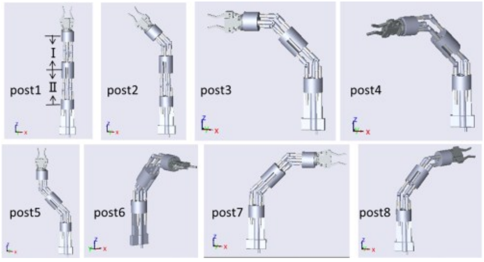
In order to enhance the stability of manipulator, the rod should longer than *8.56 mm* at the maximum bending angle. The structure of segment1 and segment2 are identical, thus, the range of each active rod is presented in table I.

TABLE I. RANGE OF EACH ACTIVE RODS' LENGTH

parameter	Rods' length (mm)			
	d_1	d_2	d_4	d_5
value	4.5-10	4.5-10	4.5-10	4.5-10

B. Simulation

Fig. 7 shows the example postures of the manipulator for approaching on surgery. According to two bending segments, the manipulator can easy attain 90° in omni-orientation. The simulation will check the dexterity of DSD mechanism, therefore, the length of translational joint and gripper are fixed in simulation. In order to insert the manipulator into body from incision, the posture of *post1* is necessary. After one segment is inserted, the gripper can bend with omni-directional motion for surgical intervention of shallow layer, the posture is as *post2*. While two segments are inserted into abdominal cavity, it will bend to several postures according to surgical requirements. In the postures of *post3, post4, post6, post7, post8*, the manipulator will bend 90° . The bending angles in each posture are shown in Fig.8.



I -segment1, II -segment2

Figure 7. Eight example postures of manipulator on surgery

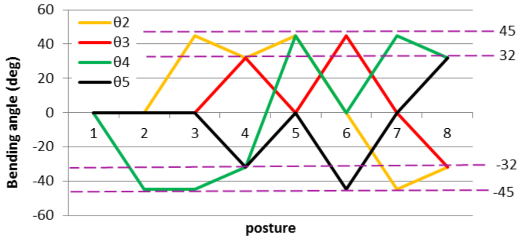


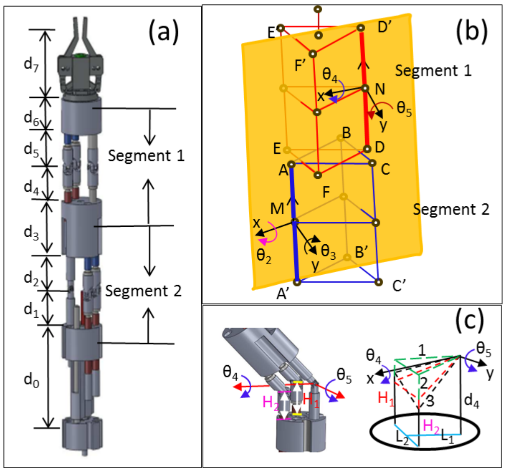
Figure 8. The relation of posture and bending angle

IV. REACTION FORCE OF FLEXIBLE SHAFT

A. Motivation

In the first prototype of manipulator, the flexible shaft will pass through segment2 to connect segment1, thus, it can simplify the flexible shaft between two segments as cantilever, one side is fixed with disk, and the other side is free.

Flexible shaft is made up of several bunches of high elastic steel wires twisted with each other. It will create reaction force when bended. Since the distance between two disks is small, the reaction force of flexible shaft was calculated when the manipulator bended. Based on the experiment result, the configuration of flexible shaft will be discussed.



θ_2 – bending angle with x axis in segment2; θ_3 – bending angle with y axis in segment2; θ_4 – bending angle with x axis in segment1; θ_5 – bending angle with y axis in segment1

(a). geometry of manipulator; (b). coordinate system of bending mechanism; (c). relation of movement diagram in segment 1

Figure 6. Nomenclature and necessary geometry of manipulator

B. Experiment setup and data analysis

The experimental setup is shown in Fig.9. Positions of marks *A,B,C* were captured by camera (shown in Fig.9(b)), A force sensor (LTS-200GA, KYOWA Cor., Japan) was used to measure the reaction force. This sensor can detect the axial force (1 DOF), its range is *2N* which is corresponded to *5V* in the display panel.

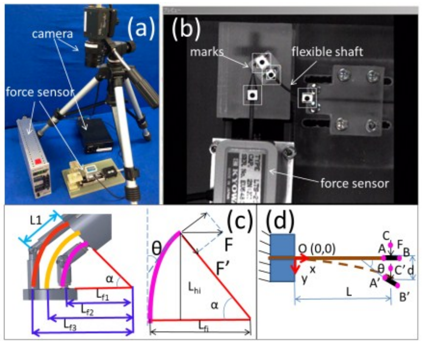
Fig.9 (d) shows the principle to calculate the Elasticity Inertia (*EI*) of flexible shaft,

$$d = \frac{FL^3}{3EI} \tag{2}$$

where, *d - displacement of the tip of flexible shaft*

F - loading force; L - the length of cantilever; EI - elasticity inertia

The relation of reaction force and displacement of flexible shaft is shown in Fig.10. Based on (2), the average EI of flexible shaft can be calculated, $EI = 1.19 \times 10^{-4} Nm^2$.



(a). experiment setup, (b). position capture scene from camera (c). bending sketch of flexible shaft, (d). principle of experiment

Figure 9. Experiment setup of reaction analysis of flexible shaft

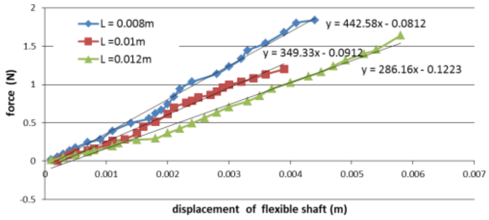


Figure 10. Relation of force and displacement of flexible shaft

The flexible shaft between disks can be simplified as circular arc, the length of L_{hi} can be given by,

$$L_{hi} = L_{fi} \cdot \sin\alpha \tag{3}$$

where, L_{hi} – *length of cantilever, i = 1,2,3*

L_{fi} – *radius of bending circle, i = 1,2,3.* α – *bending angle*

In Fig.9(c), $L_1 = 6.7mm$, when the arc angle $\alpha = 45^\circ$, we can get $L_{f1}=9.2mm$, $L_{f2}=11mm$, $L_{f3}=12.8mm$. Based on (2) and (3), the reaction force by the displacement of flexible shaft are $F_1 = 1.568N$, $F_2 = 1.094N$, $F_3 = 0.807N$.

Thus, the torque by reaction force is given by,

$$T = F_1 \cdot L_{h1} + F_2 \cdot L_{h2} + F_3 \cdot L_{h3} \tag{4}$$

When bending angle is *45 degrees*, based on (4), the torque of reaction force is $T = 0.03Nm$.

Since, the length of flexible shaft in one segment is about *10mm*, thus, the reaction force caused by flexible shaft will block manipulator for big bending movement. Furthermore, compared with no reaction force, the power from motor should be increased for bending the same angle. In order to reduce the impact of flexible shaft in power transmission, improvement was considered in the second prototype.

V. THE SECOND PROTOTYPE OF MANIPULATOR

A. Improvement of power transmission in manipulator

Principle of the bending motion in the second prototype is the same as the first prototype, however, compared with the first prototype, the flexible shaft ended at the base of the manipulator, slide block and universal joint were employed to realize power transmission, which is shown in Fig.11 (a), the screw rod can slide in the chute while transferring rotation. According to this mechanism, the power transmission mechanism can realize the bending motion due to DSD mechanism, and change its length by the slide block. The flexible shaft will not affect the bending motion of manipulator. The second prototype is shown in Fig.11 (b).

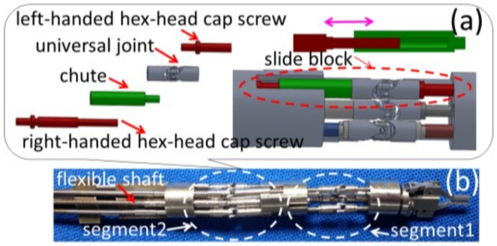
B. Motion experiments of the second prototype

Motion experiments were carried out on the second prototype of manipulator, which are shown in Fig.12. Fig.12(a) presented the experiment setup for controlling manipulator, Fig.12(b) presents the bending state of *45 deg* by segment2, Fig.12(c) presents the bending state of *90 deg* in vertical plane by two segments, Fig.12(d) presents the straight state by folding two segments, Fig.12(e) presents the bending state of *90 deg* in the level plane by two segments.

VI. CONCLUSION AND FUTURE WORK

This paper presents a novel surgical manipulator that can bend *90 deg* in any direction and has high stiffness for axial and radial loads. The proposed manipulator consists of a 1-DOF translational joint, two 2-DOF bending joints and a 1-DOF rotational gripper. Two prototypes were presented in this paper, in the first prototype, a flexible shaft connected directly the actuator to the joint, what can reduce the difficulty of assembly, but, because of the reaction force created by the bending of the flexible shaft, the motor must provide larger torque compared with the structure of the second prototype. In the second prototype, a flexible shaft is connected to the base of the manipulator. A DSD mechanism was used for power transmission. The length of rods in bending linkages can be changed automatically during bending movement. Experimental results show that the manipulator can realize dexterous movements necessary for surgical intervention.

For the future work, we will use the manipulator in vivo experiments to test the performance under surgeon's supervision. Furthermore, we will use this manipulator as dexterous arm in the Single Port Surgery.



(a). exploded state of segment 2, (b). prototype II

Figure 11. The improved power transmission mechanism

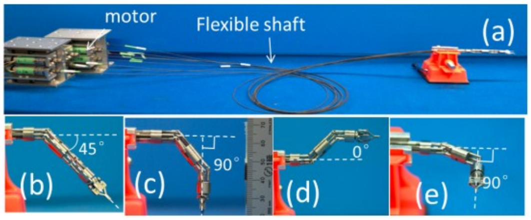


Figure 12. Motion experiments of the prototype II

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