

A Passive Snake-like Arm Based on Wire-driven Mechanism for Laparoscopic Surgery

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Abstract. In this paper, a passive snake-like arm based on wire-driven mechanism is proposed, which can be connected with remote center of motion (RCM) mechanism to form a laparoscope-holder robot and be used in laparoscopic surgery. The purpose of the snake-like arm is to replace traditional multi-joint manipulator, making it possible for the robot to assist the surgeon in the best position in a surgery. The snake-like arm consists of a main body composed of four arm units and a wire locking device with 12 wire locking units. The arm units are connected by hook hinges. Four classes force amplificatory structure is adopted in the wire locking unit. The detail structure and working principle of the wire locking device are proposed in this paper. The wire tensioning and guiding mechanism as well as the layout of wires are also introduced in this paper. Mechanical calculation of the force amplificatory structure is proposed in this paper to ensure that sufficient locking force can be provided. The workspace of the snake-like arm is drawn by simulation, and the large workspace allows the snake-like arm to be used in most laparoscopic surgeries.

1. Introduction

Laparoscopic surgery is a kind of surgery whereby the surgical operation is performed through small incisions placed on the patient's body by using some specialized instruments such as laparoscope and endoscope [1][2]. Compared to traditional open surgery, laparoscopic surgery has the advantages of low infection rate, less pain, less bleeding and quick recovery [3][4][5]. Therefore, laparoscopic surgery is called the "second revolution" of surgery. And with the continuous development and progress of robot technology, robots are gradually applied to laparoscopic surgery [6]. Compared to the hands-on surgery, robot is helpful to improve the following problems such as poor tracking performance and shaking. And the robot will not have fatigue phenomenon, thus avoiding the potential



harm to patients caused by surgeons' fatigue due to long time surgery [7].

At present, one kind of laparoscopic surgery robots is laparoscope-holder robot, such as freehand and Soloassist. The robots always combine RCM mechanism [8] and multi-joint manipulator and hold a laparoscope to assist surgeons in surgeries. There are roughly eight kinds of institutions to implement RCM at present: Isocenters, Circular Tracking Arcs, Parallelograms, Synchronous Belt Transmission, Spherical Linkages, Parallel Manipulators, Complaint Mechanisms and Passive RCM [7]. However, the mechanical arm that supports RCM mechanism is less researched, most of them are multi-joint manipulators connected by active or passive joints.

In a laparoscopic surgery, the best position for a doctor holding the laparoscope is in the rear of the surgeon, and the laparoscope should be held through the armpit of the surgeon. However, at present, most robot manipulators are difficult to achieve such operation because of their traditional driving and transmission systems. In order to solve this problem, this paper proposes a passive snake-like arm, which is used to replace traditional multi-joint manipulator and combines with RCM mechanism to form an laparoscope-holder robot. The snake-like arm is driven by wire and has the performance of rigid-flexible conversion. The high degrees-of-freedom (DOF) enables the end of the snake-like arm to reach the same point in different positions. This feature can effectively prevent interference between robot and surgeon, and even hold the laparoscope in the best position mentioned above. In Section 2, the structural design and wire layout of snake-like arm are proposed. Section 3 presents the mechanical calculation of the force amplifying structure. Section 4 shows the working space of the snake-like arm. The conclusion of this paper is given in Section 5.

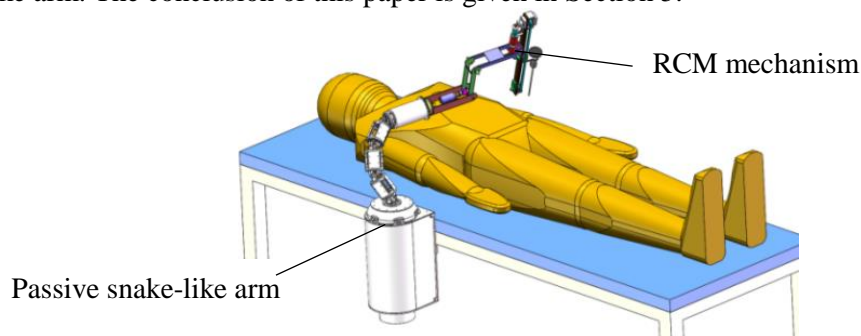


Figure 1. The overall structure of the laparoscope-holder robot

2. The structural design and wire layout of snake-like arm

The overall structure of the laparoscope-holder robot is shown in Figure 1, which contains a passive snake-like arm based on wire-driven mechanism (including the main body of the snake-like arm and a wire locking device) and RCM mechanism. Because the posture of the snake-arm is manually adjusted, the key part of the arm is the wire locking device.

2.1. The structural design of snake-like arm

2.1.1. The main body of the snake-like arm. The current design of snake-like arm generally consists of backbone (rigid or flexible), rigid universal or spherical joints, plate and wire [9]. The main body of the snake-like arm we designed [see Figure 2 (a)] use rigid backbone connected by hook hinges [see Figure 2 (c)], and contains four arm units [see Figure 2 (b)]. Each joint provides two DOFs, making the entire arm have eight DOFs. To reduce the weight of the snake-like arm, making the operation more flexible, the arm unit uses three supports to connect two guide plates instead of the whole cylinder and uses plastic as the shell. Twelve wires stretch out from the guide plate 4 and pass through the arm units through the wire guide holes. Every time a unit is passed, three wires are fixed on it. When the wires can move freely, hook hinges can rotate freely, and the surgeon can adjust the angle of the two adjacent units at will; When all wires are locked, all joints cannot move, thus fixing the posture of the snake-like arm. The main parameters of the arm are shown in Table 1.

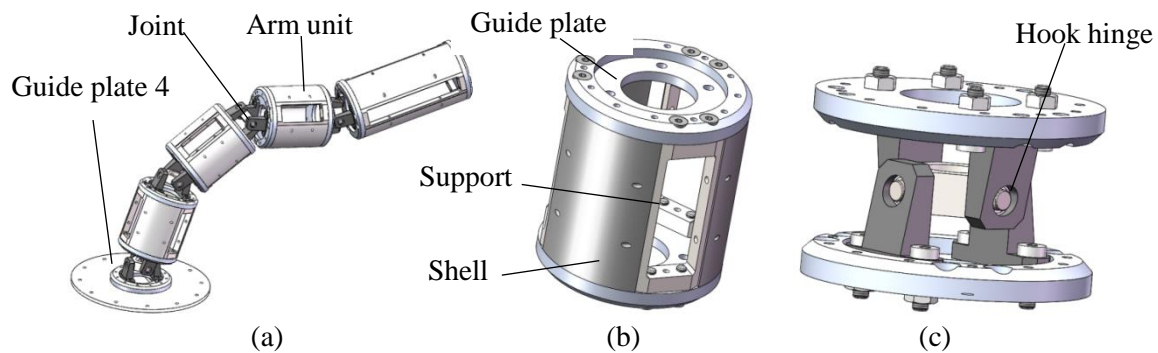


Figure 2. The main body of the snake-like arm

Table 1. Main parameters of snake-like arm

Main dimension parameter	
Length of the first three snake-like arm units (mm)	62
Length of the forth snake-like arm unit length (mm)	150
Diameter of Snake arm (mm)	55
Joint height (mm)	23
Maximum deflection Angle of Universal Joint (degree)	45 °
Total length of snake-like arm (mm)	428

2.1.2. The wire-locking device. Compared with the motor driven snake-like arm, the passive snake-like arm proposed in this paper changes the motor driving device into a wire locking device, whose overall structure is shown in Figure 3. There are 12 wire locking units, each two locking units are arranged in a row, and 6 rows are evenly distributed inside the locking device with a circumference. The stepper motor and wire guide mechanism are placed on both sides of the frame respectively. Each wire will be connected to a locking unit and then penetrated into the main body of the snake-like arm through the wire guide mechanism.

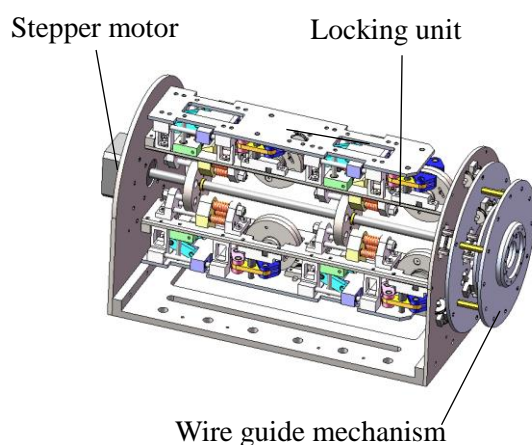


Figure 3. Wire locking device

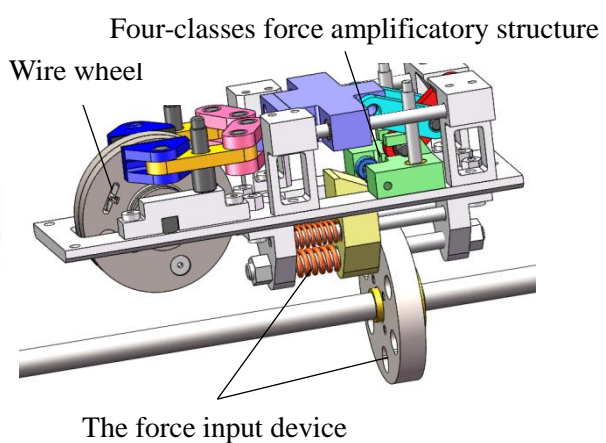


Figure 4. The structure of the locking unit

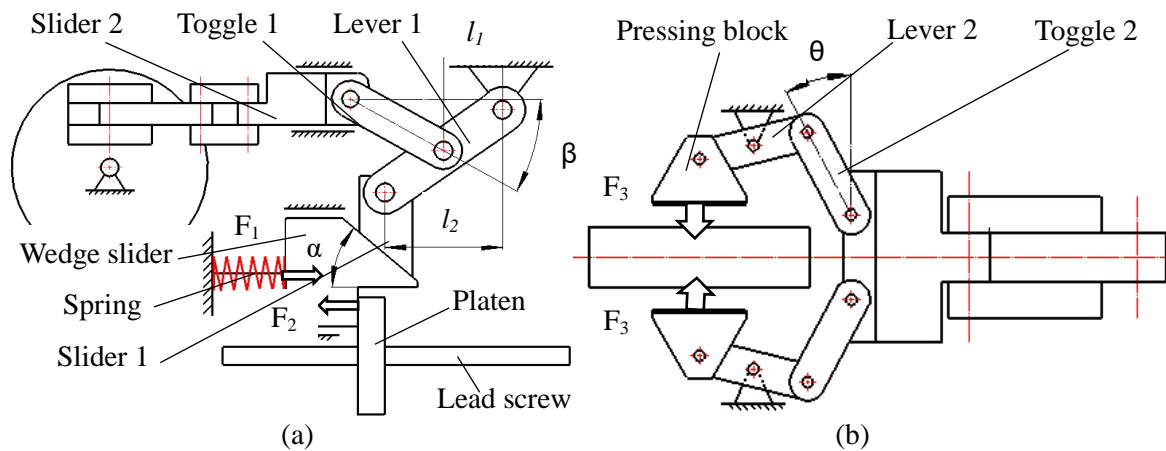


Figure 5. The working principle of the locking unit

Figure 4 shows the structure of the wire locking unit, mainly including the force input device, the four classes force amplificatory structure and the wire wheel. The force input device provides the force of locking wires and loosening wires by the compression spring and the motor respectively. The force amplificatory structure amplifies the force [10] four times to ensure that there is enough pressure to lock the wheel. Using springs instead of motor to provide input force is to maintain clamping force at all times without using force sensors, thus saving the manufacturing cost. Figure 5 shows the working principle of the locking unit. In the wire locking stage, the spring pushes the wedge slider and provides a pressure F_1 , and F_1 is amplified to F_3 by a wedge-lever-toggle-toggle-lever four classes force amplificatory structure. The wedge slider pushes the slider 1 upward to achieve the first amplification of the force; the slider 1 transfers the thrust to the toggle 1 through the permanent force increasing lever 1 to achieve the second amplification; the toggle 1 push the slider 2, making the pressure angle β reduce, and the third amplification of the force is achieved by the principle of angle amplification; the slider 2 drives the toggle 2 to reduce the pressure angle θ , achieving the fourth amplification again by the principle of angle magnification; lever 2 is an equal arm lever, which only changes the direction of the force. Finally, the pressing block is forced to tighten the wire wheel, making it impossible to rotate. Thus, wires are locked. In the loosening stage, the motor drives the lead screw to make the platen connected with the feed screw nut move to the left, pushing the wedge slider and recompressing the spring, so that the motion of the force amplificatory structure is opposite to that of the locking stage. The force on the wire wheel is removed, and the wire wheel can rotate freely, thereby enabling the wire fixed on it to move freely.

It is necessary to tighten the wire when using wire transmission. The locking unit implement the tension of the wire at the wire wheel. As shown in Figure 6(a), the wheel shaft is fixed and will not rotate, the front and rear half of the wire wheel are bolted to form a whole wire wheel rotating around the shaft. In the inner of the wire wheel, there is a power spring, and its inner and outer hooks are respectively stuck in the shaft and the wire wheel. The wire is fixed to the front half of the wheel through a wire fixing hole and twine around the wheel. In Figure 6(b), the wire wheel is rotated to make the spring tighten and store energy, so that the spring always gives the wire wheel a clockwise torque, and the wire wheel has a clockwise rotation trend under the action of this torque. Then the wire is wound counterclockwise around the wire wheel in the wire slot. When pulling the wire, the force on the wire gives a counterclockwise torque to the wire wheel. Through these two opposing torques, the steel wire gets tensioned.

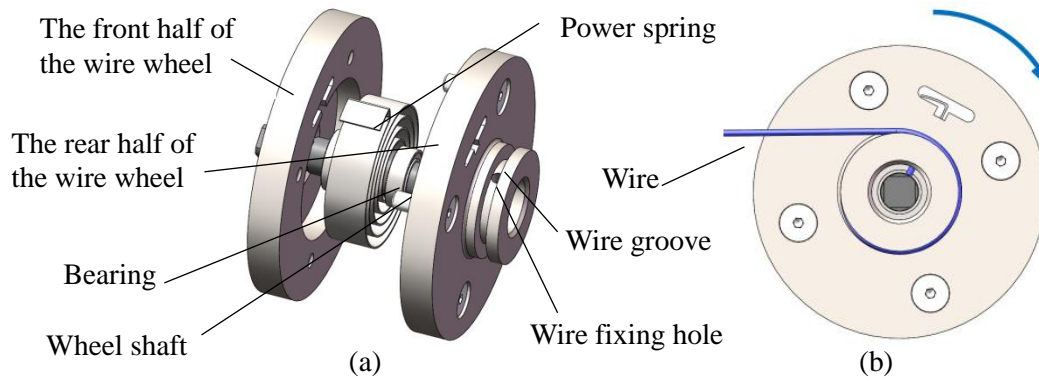


Figure 6. Wire tensioning mechanism

The diameter of the wire locking device is larger than that of the snake-like arm. To make wires penetrate into the snake-like arm without interference, a wire guide mechanism (see Figure 7) between the wire locking device and the snake-like arm is required. To avoid the permanent deformation of the wire in the transmission due to the excessive bending angle, there are 12 pulleys arranged on the guide plate 1 and 2. Also, there are 12 wire guide holes on the guide plate 3 and 4. A wire is led out by the locking unit, and penetrated into the snake-like arm by pulley 1, pulley 2, guide hole 1 and guide hole 2 respectively.

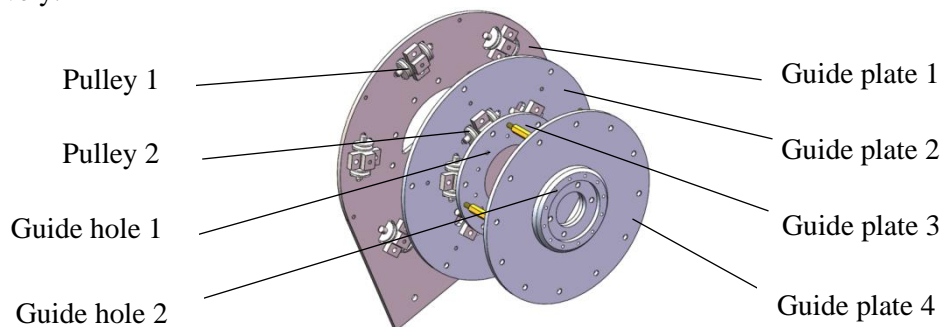


Figure 7. Wire guide mechanism

2.2. Layout design of wire

Figure 8 shows the wire layout in the wire locking device and the snake-like arm respectively. In Figure 8 (a), wires are pulled out from the left side of the front wire wheels and the right side of the rear wire wheels, the wires of the front wire wheel directly enters the guide wire mechanism, and the wires of the rear wire wheel passes through a pulley and then transmits to the wire guide mechanism. Figure 8 (b) shows the way of wire transmission in the main body of the snake-like arm. Each time a guide plate is passed, three wires distributed around the circle are fixed to it and the rest of the wires continues to go through the arm, making 12 wires pass through four arm units to achieve the wire transmission.

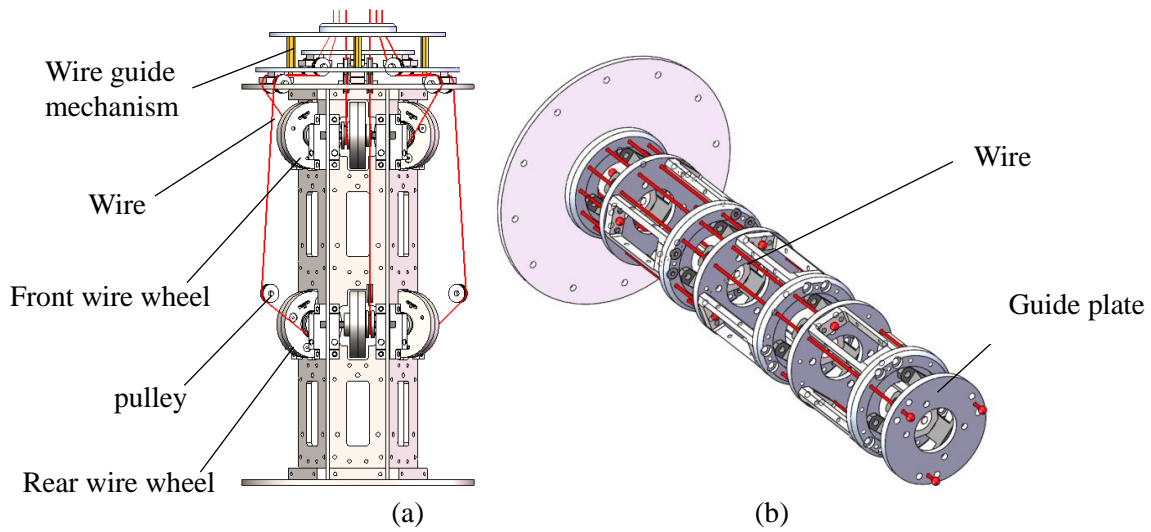


Figure 8. Layout design of wire

3. Mechanical calculation of the force amplificatory structure

Amplificatory coefficient represents the ratio of the output force to the input force. It is expressed with letter i . When the mechanical transfer efficiency and friction loss are not considered, the theoretical force augmentation coefficient and the theoretical output force are respectively expressed in symbol i_t and F_t . Through the mechanical analysis of the force amplificatory structure by Figure 5, easily obtain the result as follow.

$$\text{Theoretical force increasing coefficient: } i_t = \frac{l_2}{l_1 \tan \alpha \tan \beta \tan \theta} \quad (1)$$

$$\text{Theoretical output force: } F_t = F_1 \frac{l_2}{l_1 \tan \alpha \tan \beta \tan \theta} \quad (2)$$

Here α — dip angle of wedge slide
 β, θ — theory of pressure angle of toggle mechanism
 F_1 — the pressure of compression spring
 l_1 — active arm length of permanent force increasing lever
 l_2 — passive arm length of permanent force increasing lever

While in practical use, the actual amplificatory coefficient and the output force will be slightly different due to the existence of mechanical transfer efficiency and friction. They are expressed in symbol i_p and F_3 . They can be calculated according to the literature as follows:

$$\text{Actual force increasing coefficient: } i_p = \frac{l_2}{l_1 \tan(\alpha + \varphi_1) \tan(\beta + \varphi_2) \tan(\theta + \varphi_3)} \eta \quad (3)$$

$$\text{Actual output force: } F_3 = F_1 \frac{l_2}{n l_1 \tan(\alpha + \varphi_1) \tan(\beta + \varphi_2) \tan(\theta + \varphi_3)} \eta \quad (4)$$

Here φ_1 — friction angle between oblique planes on wedge slider
 φ_2, φ_3 — equivalent friction angle of the toggle, $\varphi = \arcsin \frac{2rf}{l}$

Where r — the radius of the hinge axis
 l — the center distance of two hinge
 f — friction factor of hinge, usually, $f = 0.1 \sim 0.15$
 η — mechanical efficiency of a lever, usually, $\eta = 0.97$
 n — number of pairs of terminal hinge pairs, $n = 2$

For this force amplificatory structure, after the wheel is pressed by the compression block, $\alpha=25^\circ$; $\beta=15^\circ$; $\theta=15^\circ$; $l_1/l_2=2$; $f=0.1$; $r_1=r_2=2.5\text{mm}$; $\varphi_1=5^\circ$; $\varphi_2=1.1^\circ$; $\varphi_3=2.3^\circ$; $\eta=0.97$. The actual force amplificatory coefficient i_p can be obtained from the formula (3) and it is about 37. It can be seen that the force increasing effect of the force amplificatory structure is very obvious. This enables the block to be pressed more tightly on the wire wheel, which is beneficial to the fixing of the snake-like arm.

4. Workspace Analysis of snake-like arm

By importing the 3D model into MATLAB and simulating the snake arm with SimMechanics in MATLAB, the workspace of the snake-like arm is generated, as shown in Figure 9. The large workspace enables the snake-like arm to reach the position of trocar in most laparoscopic surgeries to meet the needs of surgery.

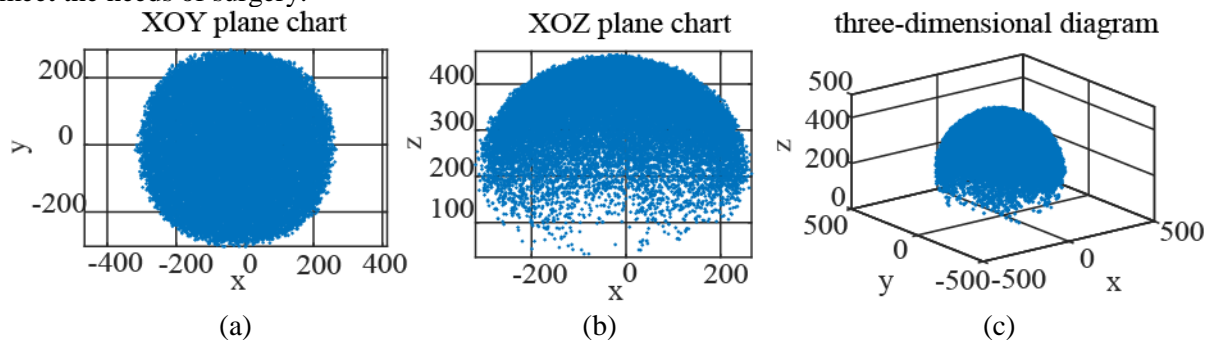


Figure 9. Workspace of snake-like arm

5. Conclusions

Based on the analysis of laparoscopic surgery, a kind of passive snake-like arm based on wire transmission is proposed to support RCM. The main body of the snake-like arm and the locking device of the wire are designed, and the input and output forces of locking wire are analyzed in order to ensure that the locking device can effectively lock the wire and make the snake-like arm become a rigid body to support the RCM. Finally, simulation analysis ensures that the snake arm can meet most of the surgical requirements.

Acknowledgments

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