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Mechanical Design of a 4-DOF Minimally Invasive Surgical Instrument*

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Abstract – **In order to meet design requirements in minimally invasive surgery (MIS), it is necessary to conduct basic operations in the narrow working space. Taking a grasper for example, a 4-DOF MIS instrument driven by servo motors and transmitted by cables is designed. The design of the end of surgical instrument driven by cables is suitable for long-distance transmission, which improves dexterity of the surgical instrument working in narrow space. The mechanism principle including the wrist, graspers and shaft rolling are described. Kinematic coupling between the wrist and grasper are analyzed. Prototype of the surgical instrument is presented. This instrument prototype can be applied in most MIS operations.**

Keywords - **Minimally invasive surgical robot; Surgical instrument; Mechanical design; Kinematic coupling; Instrument prototype.**

I. INTRODUCTION

Compared with traditional surgery, there are advantages such as smaller wound, shorter recovery time, less hospital stays and so on in minimally invasive surgery (MIS). MIS has revolutionary success in many traditional surgical domains, including cholecystectomy, prostatectomy, appendicectomy, hysterectomy, nephrectomy, Coronary artery bypass grafting and so on [1-2]. Application of robotics in MIS can ease the surgeon's weary, avoid surgeon's hand tremble, enhance flexibility of the instrument and realization of telesurgery. The most representative surgical robot system is da Vinci system developed by Intuitive Surgical Inc. in the US, which has sold more than 4, 986 sets by the end of 2018 [3].

As the end-effector of the minimally invasive surgical robot (MISR), surgical instruments replace all functions of surgical instruments directly held by the surgeon in traditional MIS. Generally, the end-effector of the surgical instruments should be designed to complete grasping, cutting, shearing, pinching and other motions like the human's hands. Researchers domestic and abroad have done a lot of work in this area.

The instrument of "MicroHand A" system in Tianjin University has 3 or 4 DOFs, and the instrument can realize full dimensional motion together with the slave manipulator. External diameter of the instruments is 8mm. Maximum range in both pitch and yaw are ±90°. The range in roll is ±270°. Fast change interface is designed in the end of slave manipulator, using this interface, the surgical instruments on the slave manipulator can be installed and removed quickly in 20 seconds without extra tool or power [4].

A forceps with snake-like and modular design is developed for an abdominal MISR in HIT. The forceps has 7 DOFs, motions required by all kinds of surgeries can be completed, such as rolling of the instrument shaft, pitch and yaw of the wrist, gripping of the forceps. Besides, surgical instrument can be reliably connected by fast changing interface. However, the length of combination of wrist and forceps mechanism is 70 mm. Comparing with the limited distance between lesion point and insertion point of the trocar in abdominal operation, 70mm is too long. Therefore, clinical application of this instrument is seriously limited [5].

In order to solve cable loosening that is easy to occur in surgical instruments during transmission, J. Arata in Nagoya University of Technology takes advantage of servo motor and rigid rods instead of cable transmission. Transmission accuracy caused by cable transmission is partly avoided, but application of rigid rods in surgical instruments leads to cumbersome volume, which is more difficult in transmission and control [6].

A surgical instrument named AMMIS with high sensitivity was designed by M. Minor in Michigan State University. Application of compact gear mechanism in AMMIS has many advantages, such as stable transmission, more positioning accuracy, constant transmission ratio and so on. Therefore, tremor of hand and scaling ratio of motion can be preferably solved. This special structure provides a bigger workspace, less shock, higher stiffness, greater load-bearing capacity and longer working time. In order to meet performance mentioned above, selecting the contour and shape of the rod and other factors should be considered reasonably [7].

In order to improve dexterity of the surgical instrument which is deeply inserted into the throat, a set of modular joints (distal dexterous units) was designed by N. Simaan in Columbia University. This modular joint consists of two sets of snake-like assembly, which can provide 4 DOF motion for the instrument. Although the sensitivity is improved, the specially designed control algorithm involving kinematics of continuum mechanism and elimination of flexibility and backlash in the driving chain is seriously limited [8].

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Endowrist developed by Intuitive Surgical Inc. is most widely used nowadays. It is able to imitate the dexterous motion of a human's hands with 4 DOFs in roll, pitch, yaw, open and close. Taking advantage of "N+1" driving methods (N+1 motors drive N DOFs) by cable transmission, joints of the surgical instrument are controlled by driving lines connected to four capstans, and motions of motors are transmitted to cables using the four capstans located in the instrument house. However, the actuation platform of Endowrist is connected to remote center mechanism (RCM), it leads to bigger volume and mass, and unease to take [9].

In this paper, mechanical design of a 4-DOF surgical instrument and actuation platform is presented. Contributions of this paper include mechanism synthesis of 4-DOF surgical instruments, driving and transmission system of the surgical instruments, and design of the actuation platform. Innovative design of MIS instrument is focused, and mechanism synthesis, transmission system, instrument prototype are highlighted in this paper.

II. Mechanism Synthesis of Surgical Instrument

Basic technical operations in MIS include gripping, shearing, dissection, suturing, knotting, and sturing and knotting are the most important and complex technical operations. Meanwhile, as the most effective means of haemostasis in surgery, grasper is most frequently used in surgery. As a result, grasper is used as an example to design MIS instrument in this paper.

Surgical instruments are all inserted into the abdominal cavity through 10 mm inner-diameter trocars which are placed in the patient's abdominal wound. Taking the wound as a fulcrum, three rotational motions and one translational motion along the axis of instruments should be arranged. Workspace is an inverted conical taking the wound as a vertex. Workspace of the surgical instrument are controlled directly by the adjust the angles and linear displacement of the instrument. Operation mode of MIS instrument is shown in Fig. 1.

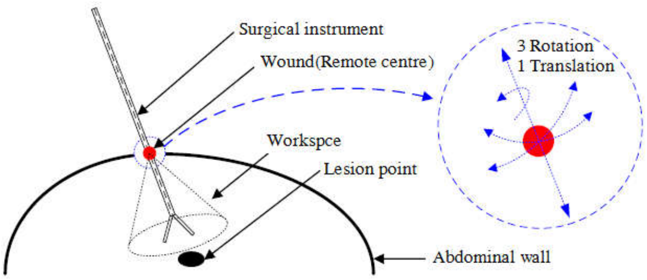

Fig. 1 Operation mode of MIS instrument

From Fig. 1, 2 DOFS of the instrument are limited by the wound, which influences the dexterity of the instrument and contradicts to requirement of operation in confined space of abdominal cavity. In order to conduct all kinds of technical operations, appropriate configurations should be considered seriously to restore the lost DOF in the wound [10].

RCM of the MISR can provide 2 DOFs in rotation and 1 DOF in translation along the instrument axis. Using three DOFs above, position adjustment of the end of surgical instrument can be realized in workspace of the instrument. In addition, there are 3 DOFs of orientation and 1 DOF of gripping are needed. As a result, operations of the surgical instrument in any position and orientation in the workspace can be guaranteed. In consideration of the requirements for orientations of the surgical instrument, the most effective method is to add wrist mechanism to traditional surgical instrument, so pitch and yaw motions can be completed. The wrist mechanism is presented firstly in this paper.

A. Design of Wrist and Grasper

Considering requirements of smaller inertia to improve flexibility and adaptability to long distance transmission for the instrument end, combination of motors and cables are used in driving unit. If linear motion joints are applied, conversion between the linear displacement and rotational degree will be more complex than application of rotational joints. In order to reduce size of the driving unit and realize precise control, rotation joints are used in mechanism design of instrument end. The end of surgical instrument consists of shaft, connector, wrist and graspers, the wrist is shown in Fig. 2.

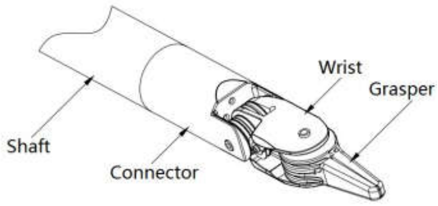

Fig 2 Structure diagram of the wrist

The wrist is a platform that carries all the transmission wheels in design of the instrument end, wrist fixed wheel, wrist guide wheels and grasper guide wheels are fixed on this platform by pins. The transmission system of the wrist is shown in Fig. 3. In order to meet requirements of MIS, smaller size of the instrument end is designed. Maximum size in radial and axial directions are 10 mm and 30 mm respectively. In order to provide stable connection and accurate transmission, transition fit is used between each guide wheel and pin, and interference fit is used between pins and wrist in the narrow space of the wrist. Wrist guide wheels and grasper guide wheels are used to guide the cables that control the motion of the instrument end. Reliability and dexterity of motions of the graspers are ensured by placing the guide wheels in an appropriate position.

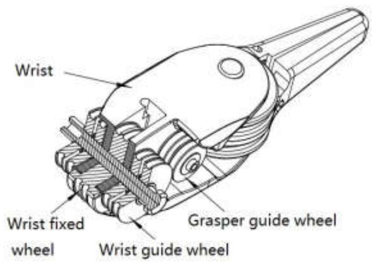

Fig. 3 Transmission system of the wrist

In order to keep the radius of gyration unchanged when the cables move around the axis of wrist and increase the accuracy of motion, the wrist guide wheels are designed. At the same time, in order to adapt the existing machining conditions and overcome the difficulty in machining arc characteristic in internal parts, the wrist and wrist fixed wheel are separated into two parts. Machining difficulty is reduced and machining accuracy of the wheel groove is ensured. Fig. 4 shows assembly of wrist and fixed wheel.

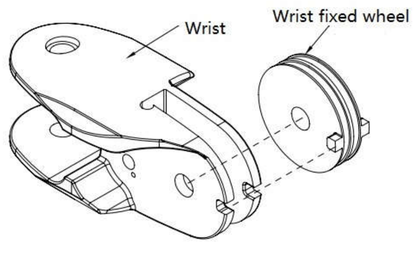

Fig. 4 Assembly of wrist and wrist fixed wheel

Considering the graspers are usually closed, open degree of the graspers should be designed to suit the size of most lesion tissues. Moreover, gripping force (approximately 2 N) is also required in MIS. Graspers are consisted of two blades. Pins and the grooves are designed to limit the opening and closing degrees. Maximal opening degree is 90, which is enough to suit the sizes of most lesion tissues. Structure features of the graspers are shown in Fig. 5. Cable groove is used to guide the cables, and fixed end along the grooves is used to control the motion of the graspers. In order to ensure stable gripping and avoid difficulty in closing the graspers, a dip angle of 1 degree for the two blades relative to interior material is designed. At the same time, the micro elastic deformation is created to strengthen the gripping forces in closing the end of graspers.

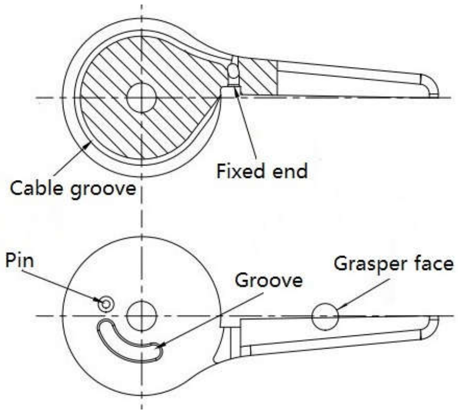

Fig. 5 Structure features of the graspers

B. *Design of Rolling Mechanism*

This mechanism is designed to realize the rotational DOF of the surgical instrument along the instrument axis. The end of this mechanism is connected to the wrist to realize rotation of instrument end in abdominal cavity, which is very important in most surgical operations such as location, suturing and knotting. Rolling mechanism consists of shaft wheel, shaft, sleeve, bearing, cover and base of bearing. Shaft wheel is designed to wrap the cables. Two reversely wrapped cables driving by one motor is applied to complete rotation in two reverse directions. External diameter of the shaft is 10 mm, length of the shaft is 424 mm, which provides long insertion depth into abdominal cavity. The rolling mechanism of the instrument is shown in Fig. 6.

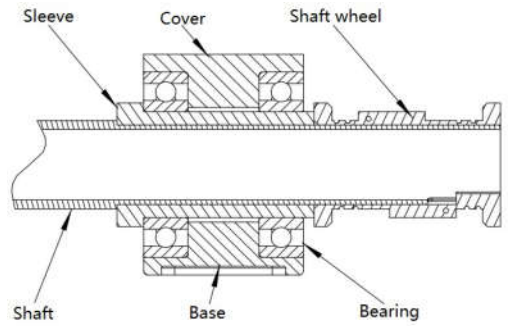

Fig. 6 Rolling mechanism of the shaft

III. DRIVE SYSTEM OF SURGICAL INSTRUMENT

Smaller size of the end of surgical instrument is needed according to the requirements of MIS. Capstan and cables is suitable for long distance and flexible transmission. Therefore, placing the driving source far away from the end of the surgical instruments is available. The cables driving the instrument end are all guided through the long and thin instrument shaft.

A. *Introduction to Transmission System*

As shown in Fig. 7, transmission system of the instrument shaft consists of shaft capstan, shaft head and cables. Two reversely wrapped cables are guided from the shaft head to the grooves shaft capstan. The shaft capstan is driven by a DC motor, force and motion are generated by cable transmission. One cable takes in the shaft head and another cable runs reversely which ensures the continuity of motion. The shaft head is installed in the rolling mechanism, which transmits the rotation to the whole surgical instrument.

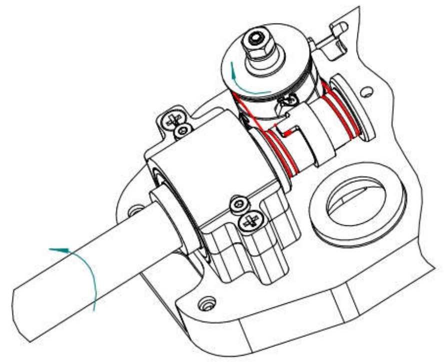
Fig 7 Transmission system of the shaft

As shown in Fig. 8, transmission system of the wrist consists of capstan, guide wheels and cables. Cable 1 and 2 are wrapped in reverse directions on the capstan. In order to overcome space limitations of the transmission mechanism, several guide wheels are designed to guide the cables straight into the instrument shaft. And the cables are extracted through the connector and applied to drive the wrist.

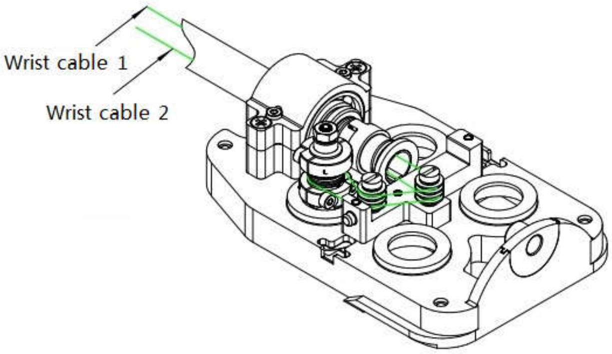

Fig 8 Transmission system of the wrist

As shown in Fig. 9, transmission system of the graspers consists of two blades. Mechanism design of transmission system for each blade is the same as the wrist. Four motion modes of the graspers can be realized by controlling directions of two capstans. Because the cables in transmission system of the graspers and wrist are guided into the shaft by the guide wheels, guide wheels are designed inconsistently in height. Therefore, cross between the cables are avoided, loss of cables are reduced, and service life of cables are extended.

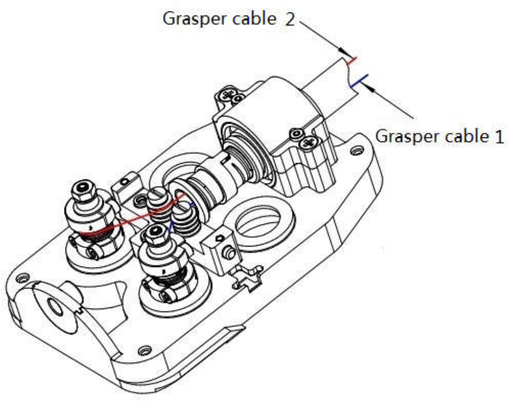

Fig 9 Transmission system of the graspers

B. Kinematic Coupling Analysis of Wrist and Graspers

In order to ensure flexibility of the surgical instrument in narrow space, 4 DOFs of motion must be integrated in this mechanism. An overall consideration should be made between smaller size of the instrument end and complex layout of transmission mechanism.

Cable transmission with lighter weight and long distance transmission is applied, and a series of rotational joints is used. Cables driving the graspers are guided from transmission system through the shaft and connector to the grooves and fixed in fixed end. The cables used to drive the instrument end is shown in Fig. 10.

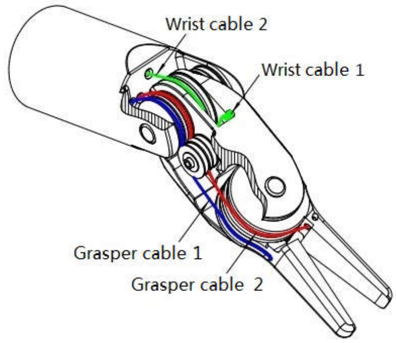

Fig. 10 Cables applied to drive the instrument end

As shown in Fig. 11(a), supposing radius of the wrist guide wheel is R_1 and rotational radius of the grasper groove is R_2. When the instrument end coincides with the shaft axis, the wrapped angle generated by the cable and wrist guide wheels is denoted by α, and the graspers are closed just right.

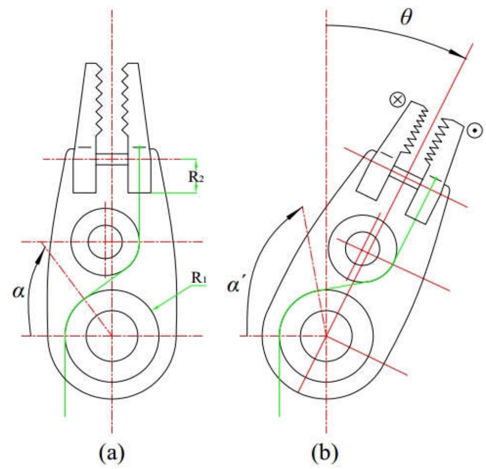

Fig. 11 Kinematic coupling between the wrist and graspers

When the wrist rotates a degree θ, the diagram after rotation is shown in Fig. 11(b). At present, the wrapped angle generated by the cable and wrist guide wheel is denoted by α',

$$\alpha' = \theta + \alpha \tag{1}$$

or

$$\theta = \alpha' - \alpha \tag{2}$$

And length change on the cable and wrist guide wheel is

$$\Delta L = (\alpha' - \alpha) \cdot R_1 = \theta \cdot R_1 \tag{3}$$

There is no transmission effect in the graspers because of no motion in the grasper driving system. Therefore, kinematic coupling is produced by cable length change in the wrist guide wheels. The coupling angle is derived as

$$\varphi = \frac{\Delta L}{R_2} = \frac{R_1}{R_2} \cdot \theta \tag{4}$$

Base on analysis above, φ is proportional to R_1 and θ, and in inverse proportion to R_2. If rotational angle of the wrist is unchanged, the coupling angle can be reduced as long as R_1 is less than R_2. In addition, if R_1 equals to 0, which means that cable passes through pins in the wrist along the radial direction. It needs to produce holes in pins for cables to pass through. Above all, strength of pins is greatly reduced, and it is harmful in operation.

In order to eliminate the kinematic coupling, it is preferable to apply motion compensation rather than mechanism redesign. According to the coupling analysis, when the wrist rotates, driving motor of the graspers rotates about a certain angle to compensate the coupling angle. In this way, decoupling can be completed by the control algorithm in software to design integrity for the surgical instrument.

IV. INSTRUMENT PROTOTYPE

According to mechanism and transmission system of MIS instrument mentioned above, the prototype of surgical instrument is fabricated and presented in Fig. 12. Length of the surgical instrument is 512 mm and external diameter is 10mm. Stainless steel is utilized to manufacture the instrument end that contacts the human body.

Fig. 12 Prototype of the surgical instrument

In addition, flexible cables are used to transmit motions, which reduces harmful effect to human body. The MIS instrument with good biocompatibility is fabricated. The transmission system consists of shaft rolling mechanism, wrist mechanism of, graspers is shown in Fig. 13.

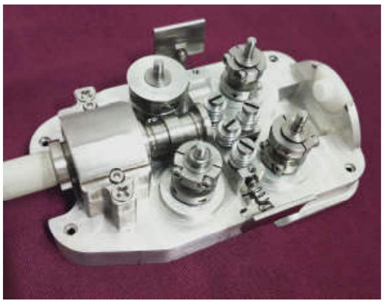

Fig. 13 Transmission system of the surgical instrument

In order to display the mechanism design of the instrument end, the detail of the instrument end is shown in Figure 14. The instrument end is used to conduct all kinds of surgical operations. The most important parts are graspers that can realize pitch, yaw, open and close motions.

Fig 14 The motions of the instrument end

Prototype of the surgical instrument is connected to a actuation platform, motions are output from the actuation platform to surgical instrument to conduct the motions with 4 DOFs. Connection between instrument and actuation platform is shown in Fig. 15.

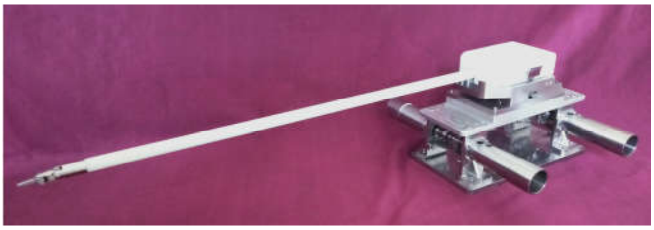

Fig. 15 Surgical instrument connected to actuation platform

V. DISCUSSION

According to mechanism design, kinematic analysis and instrument prototype descided above, main functions and important mechanism are introduced in detail. What's more, in order to display the contribution and significance comparing with other surgical instruments, Table I summarizes differences between our design and previous works.

TABLE I COMPARISON BETWEEN OUR DESIGN AND PREVIOUS WORKS

	Appearance				
	DOF	Size	Drive	Coupling	Wrist feature
Endowrist	4	5-8 mm	Cable	Yes	No
TJU	4	10 mm	Cable	Yes	No
HIT	4	10 mm	Cable	Yes	No
J. Arata	4	10 mm	Rigid rod	No	Rigid rod
AMMIS	4	>10 mm	Gear	No	Gear
N. Simaan	4	<10 mm	Cable	Yes	No
Our design	4	10mm	Cable	Yes	Fixed wheel

By comparisons in Table I, significance in this 4-DOF MIS instrument is design and application of the wrist fixed wheel. As mentioned above, machining difficulty is reduced and machining accuracy of the wheel groove is ensured using wrist fixed wheel. Therefore, it provides a good effect on improving control accuracy of the wrist and end of the surgical instrument. On the other hand, our work promotes technology innovations of minimally invasive surgical robot in our country.

VI. CONCLUSION

A 4-DOF MIS instrument is designed in this paper. According to the requirement in MIS, Mechanism design including shaft rolling, pitch of the wrist, yaw of the wrist, opening and closing of the graspers are presented. In order to reduce the weight of surgical instrument and realize long distance transmission, cable transmission is utilized in driving system. Kinematic coupling between wrist and graspers is analysed. Prototype of this surgical instrument is presented.

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