Pneumatically-Driven 4-DOF Surgical Manipulator with a Separation Mechanism using Cranks

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Abstract. In this paper, we developed a novel mechanism for a pneumatically-driven surgical robot, which enables attachment of the unsterilizable drive part and the sterilizable forceps part. Since pneumatic cylinders generate linear motion, the proposed robotic forceps has crank mechanisms to convert the linear pushing force of cylinders to the tension of stainless wires. A magnet couples the cylinder and the crank rod, which enables easy attachment without fastening mechanisms. Using the proposed mechanism, we prototyped a four-degrees-of-freedom forceps manipulator having two-DOF flexible elbow and wrist joints. Six pairs of the cylinder and the crank drive these degrees of freedom. We also introduced a low-cost position sensor for servo control of the cylinders. Preliminary experiments are conducted to see the static characteristics of the transmission mechanism and the flexible joint and the position sensor.

Keywords: Surgical robot, Pneumatic system, Sterilization

INTRODUCTION

Laparoscopic surgery is a popular surgical method, which leaves smaller incision scars to the patient and shortens the hospitalization period. Reduction of damage to the patients is achieved by much fatigue of surgeons, since operations must be conducted through small holes on the patients' skin, using long laparoscopic forceps and a camera with a narrow field of view.

Surgical robots have been developed to increase the efficiency of laparoscopic surgery [1-3]. Such robots were actuated by electric motors or pneumatic actuators. Since surgical tools must be washed and sterilized before surgery, surgical robots have mechanisms which allow separation of sterilizable forceps part and unsterilizable driving unit with actuators. However, existing mechanisms transmit rotational motion of electric motors. Pneumatic actuators usually generate linear motion. Conventional separation mechanisms for transmitting linear motion require users to mechanically couple the two units, and it also requires precisely manufactured parts.

When the degree-of-freedom of the forceps gets higher, it becomes harder to attach the drive unit and the forceps unit because multiple mechanical contacts must be coupled at once. For example, a 4-DOF forceps [4] reduces the robot motion outside the patient's abdominal cavity, since a 2-DOF outside holder robot is theoretically enough. It is also applicable to single-port surgery and Natural Orifice Translumenal Endoscopic Surgery (NOTES). We have developed a 4-DOF forceps manipulator driven by pneumatic cylinders [5]. However, the separation of drive and forceps units in the 4-DOF forceps was difficult and not implemented. The multi-DOF forceps by Goldman et. al. [6] is separatable, but it adopts rotational electric motor.

In this work, a separation mechanism using cranks and magnetic connectors for a wire-driven surgical manipulator, which is suitable for pneumatically-driven robots, is proposed. It converts the linear motion of pneumatic cylinder to the rotational motion to pull the driving wire. We designed a four-DOF manipulator using the proposed mechanism and constructed a prototype system.

SEPARATION MECHANISM FOR PNEUMATIC SURGICAL MANIPULATOR

Requirement for Separation in Surgical Robot

Most of surgical robot systems have separation mechanisms. Typical surgical manipulator consists of a forceps unit and a drive unit. The forceps unit has minimal mechanical and electrical parts so that it can be sterilized using an autoclave or ethylene oxide gas. The drive unit has actuators and sensors, which are not washed or sterilized. A drape covers the drive unit to prevent the invasion of bacteria into the forceps. Usually, a disposable sterilization adapter provides the function of separating them while transmitting driving forces between them.

The Proposed Mechanism

Figure 1 shows the proposed mechanism. The forceps unit has crank mechanisms. A stainless wire, which drives the wrist and elbow joints of the forceps, is fixed to the pulley and a magnetic connector is attached to the crank link. In the drive unit, a magnetic connector is mounted on the tip of a pneumatic cylinder. The magnetic connector couples the drive unit and the forceps unit, and the pushing force of the pneumatic cylinder is converted to the tension of the wire to drive the forceps joint. The main function of the magnet is to align the both units when coupling, and it is not necessary for the magnets to transmit a pulling force. This mechanism has following features:

- The coupling only has to transmit pushing forces, and mechanical connection is not required.
- Pushing force transmission is suitable for pneumatic systems since the cross-sectional area of a single rod cylinder is larger for pushing direction than pulling direction.
- Design parameter of the forceps, such as outer diameter, can be changed by only modifying the cranks, without re-designing the drive unit. This feature can also make the forceps easily interchangeable.
- Sterilization adapter is not necessary. The mechanism can transmit the driving force over the drape.

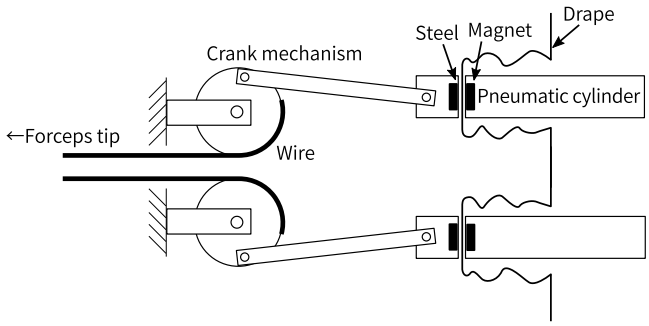

FIGURE 1. The proposed separation mechanism

FOUR-DOF SURGICAL MANIPULATOR

Mechanical Design

We developed a four-degree-of-freedom surgical manipulator using the proposed separation mechanism. Compared to the conventional 2-DOF manipulator with a wrist, a 4-DOF manipulator can translationally move inside the patient body without swinging the holder robot outside, as shown in Fig. 2. The prototype is shown in Fig. 3. The manipulator is ø8mm in outer diameter. It has two flexible joints made of stainless machined spring. Each of the joints is driven by three wires connected to pneumatic cylinders (SMC CJ2XB16-10Z) in the drive unit. The drive unit has one additional cylinder in the center for future extension.

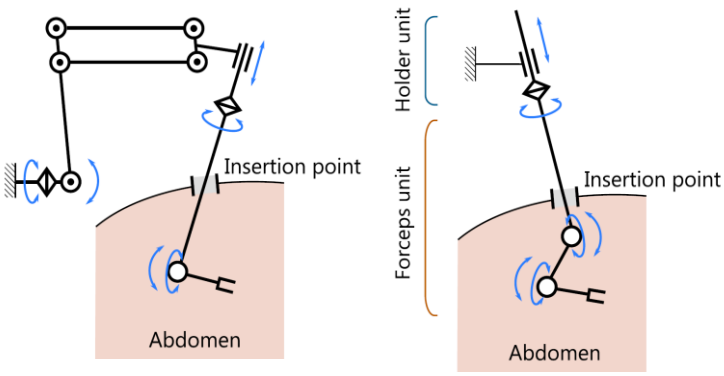

FIGURE 2. 2-DOF forceps and 4-DOF forceps.

FIGURE 3. 4-DOF Surgical manipulator.

Design of Position Sensor

The 4-DOF manipulator has a link of length 50 mm after the flexible joint. The displacement of the manipulator tip is about 17 times of that of the cylinder. Thus a high-resolution, compact, and low-cost position sensor is desired.
We adopted a magnetic encoder chip (AMS AS5311). The sensor has the resolution of 500 nm. We prototyped the sensor board with the encoder IC, a differential driver, and some noise filters, shown in Fig. 4. The dimension of the sensor board is 12mm x 20mm x 3mm.

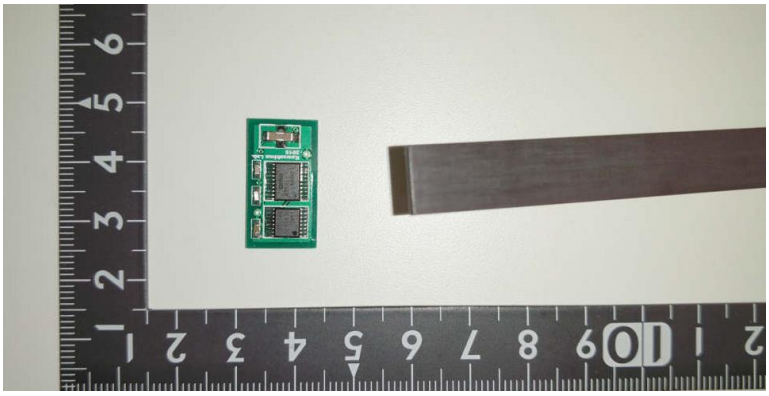

FIGURE 4. The as5311-based position sensor (left) and magnet strips (right).
The magnet strips should be cut to an appropriate length.

EVALUATION

Coupling of Drive and Forceps Units

We tried the assembling of the drive unit and the forceps unit. Since the proposed magnetic coupling does not require mechanical coupling procedure, the coupling itself is completed in 5 seconds. However, it took a long time to fasten the bolts and wing nuts to lock the two units. It should be replaced with a more quick connecting mechanism.

Static Characteristics

We observed the static characteristics of the forceps manipulator. At first, one cylinder, which drives the elbow joint, is activated and the angle of the wrist joint is measured. A cylinder applied stepwise driving force to the transmission mechanism. The step size is 2 [N], and the maximum driving force is 20 [N]. The interval between the steps is 5 [sec]. To observe the hysteresis, we applied both upward force from 0 to 20 [N] and downward force from 20[N] to 0 [N]. Additionally, all cylinders applied 1 [N] driving force to keep the wire tension. A video camera captured the forceps as shown in Fig. 5, and the joint angle is measured using an image processing software Gimp 2.8.

Figure 6. shows the experimental result. Hysteresis is observed, but the relationship between the driving force and the joint angle is linearly increasing. The main cause of the hysteresis is the plastic pipe used as the backbone of the flexible joint.
Then, we evaluated the wrist joint. A cylinder for the wrist joint is activated, and the experiment is conducted in a similar way. The result is shown in Fig. 7. Both the elbow and wrist joints bent, since the wire applies the same amount of bending torque to the elbow joint. The displacement of the elbow is larger than that in the previous experiment. This difference may be caused by the difference of wire path.

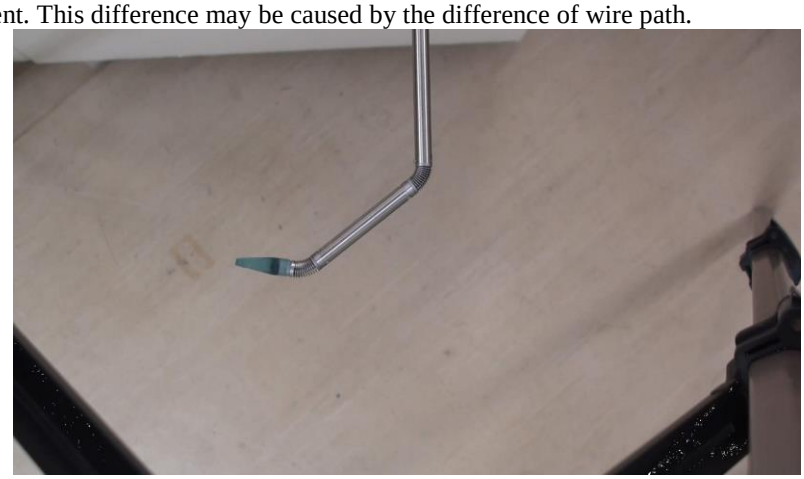

FIGURE 5. Experiment image recorded by a camera.

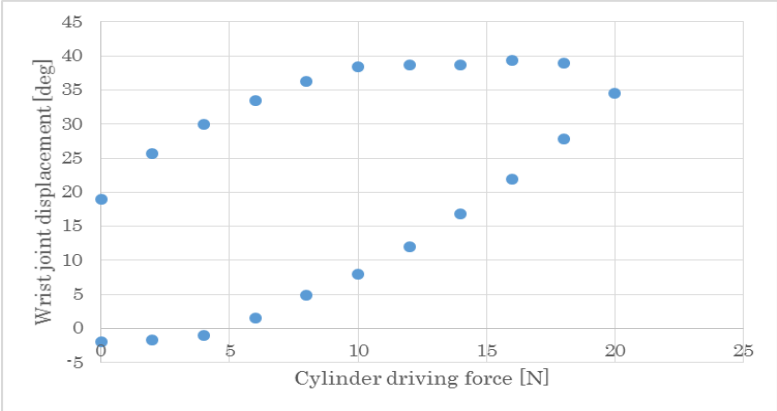

FIGURE 6. Joint angle when actuating elbow cylinder.

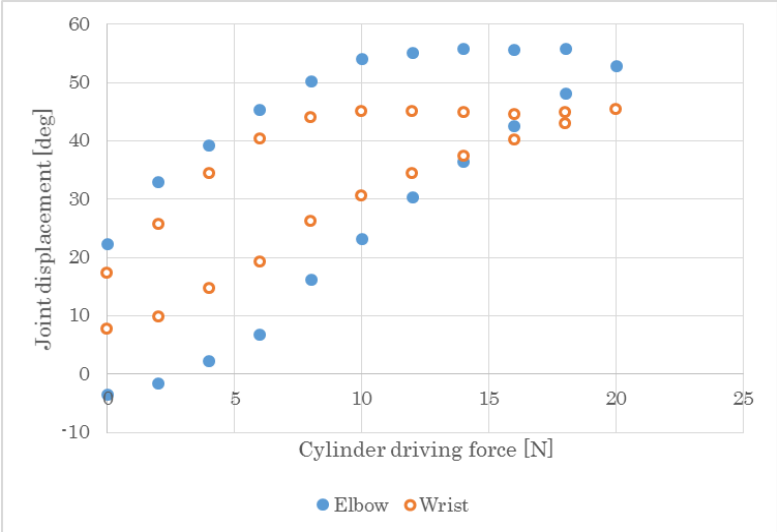

FIGURE 7. Joint angle when actuating wrist cylinder.

Performance of Position Sensor

The position sensor is evaluated by a laser displacement sensor (Keyence LK-G3000). The position sensor is attached to the cylinder of the drive unit and the laser measured the cylinder displacement. Figure 8 shows the measurement error. The error is about 0.25% F.S. Reproducible sinusoidal error is observed, which can be compensated for to increase accuracy. There is 20 [um] hysteresis at maximum. The source of this hysteresis is the noise filter implemented in the sensor IC.

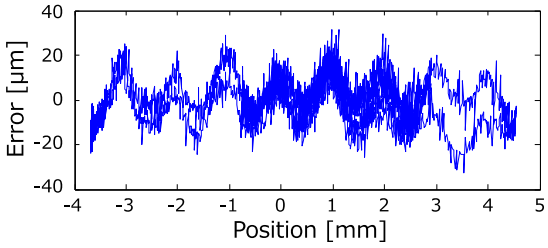

FIGURE 8. The performance of a magnetic position sensor.

CONCLUSION

We developed a surgical manipulator driven by pneumatic cylinders. A separation mechanism suitable for a linear actuator, which consists of magnetic couplers and crank mechanism, is proposed. We also designed and evaluated a low-cost and high-resolution position sensor for precise motion control.

ACKNOWLEDGMENTS

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