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Design and Analysis of a Novel Articulated Drive Mechanism for Multifunctional NOTES Robot

This paper presents a novel articulated drive mechanism (ADM) for a multifunctional natural orifice transluminal endoscopic surgery (NOTES) robotic manipulator. It consists mainly of three major components including a snakelike linkage, motor housing, and an arm connector. The ADM can articulate into complex shapes for improved access to surgical targets. A connector provides an efficient and convenient modularity for insertion and removal of the robot. Four DC motors guide eight cables to steer the robot. The workspace, cable displacement and force transmission relationships are derived. Experimental results give preliminary validation of the feasibility and capability of the ADM system. [DOI: 10.1115/1.4029307]

Keywords: articulated drive mechanism, NOTES, multifunctional robot, cable displacement

1 Introduction

Minimally invasive surgery (MIS) refers to performance of internal cavity (e.g., abdominal) surgery through smaller incisions to reduce recovery time and minimize aesthetic damage [1]. Due to its various advantages, such as less postoperative morbidity, shortened hospitalization, and cosmetic improvement [2], MIS is preferred by many patients and has seen rapid growth since the first report of laparoscopic cholecystectomy in the mid-1980s.

NOTES, an emerging technique, passes the instrument through a natural orifice (e.g., vagina, anus, or esophagus) and gains access to the peritoneal cavity through an internal tissue incision. Compared with open surgery and traditional MIS, the lack of external skin incisions during NOTES provides patients with more potential advantages such as no visible scarring, less postoperative pain and a lower anesthesia requirement [3]. In addition, several natural orifices with different advantages for different kinds of NOTES procedures provide surgeons with multiple choices according to the specific surgical requirements [4]. The first test of NOTES was performed on a porcine model by Kalloo et al. [5], and human NOTES shortly followed [6]. According to the statistics in Ref. [4], 916 patients received NOTES by 2012 worldwide, 79% of which were transvaginal NOTES. Although NOTES is appealing for patients, its prevalence in practical clinical human surgeries is challenged by a number of constraints, including constraints fundamental to the NOTES approach (e.g., limited space), as well as constraints related to the surgical tools, such as unstable actuation devices, weak tool tips, lack of visual/tool triangulation, and lack

of dexterous multitasking tools [7]. To address these problems, many researchers have pursued various medical devices for NOTES. Most of these devices are designed with a snakelike structure.

Shang et al. [8] designed a snakelike articulated robot with 7DOF (degrees of freedom) based on universal joints. It is actuated by seven small onboard motors. Two internal channels provide access ports for a camera and a surgical instrument. Both single-incision laparoscopic surgery and transvaginal NOTES were tested on a porcine model and an optimistic result was obtained. However, the sustainable levels of force and torque were not sufficient for more complicated NOTES procedures. Furthermore, fabrication of its tiny universal joints was difficult and costly.

Olympus provides a commercial “R” scope which has two independent curvature sections and works with two instrument channels accommodating standard flexible endoscopic tools. The primary flexure of the two bendable segments can be locked and simultaneously leave the tips to conduct independent motion [9]. However, to operate this system requires several surgeons in cooperation. Moreover, the limited workspace restrains its use in aggressive retraction [2].

Degani et al. [10] designed a highly articulated robotic probe with inner and outer snakelike tubes for MIS. By alternating the tubes between limp and rigid modes, the head of the robot can be steered and place the robot to the desired target. Although experiments verified that the robot could achieve different trajectories, it just has one curvature section, and a proper end effector remained to be implemented.

Bajo et al. [11] designed a bimanual snakelike robotic effector platform for single-port surgery. Each arm has 7DOF with which to create complicated shapes. It has strong potential to be used in NOTES as long as the problems of complicated control and limited workspace can be solved.

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Fig. 1 Model and prototype of the robotic platform

As these snakelike robots are usually underactuated or redundant, appropriate kinematic analysis is requisite for controller design. Li et al. [12] designed a continuous backbone cable-driven robot and analyzed the nonlinear kinematics of the system. Although the nonlinear solution was demonstrated to be efficient, it may not be suitable for other snakelike robots without elastic linkages. In Ref. [13], Kim et al. presented a snakelike surgical robot with two curvature sections. Its motion was based on a length-invariant neutral line and used rolling-contact joints with special geometry to achieve this. Due to this design strategy, the kinematic analysis is not directly extensible to other robots with simpler pin joints. Lehman et al. [14] designed a bimanual robot entering the peritoneal cavity through the esophagus. A magnetic anchoring system outside the skin was used to orient the robot. On-board cameras and complementary endoscope provide the surgeons with sufficient visual feedback. However, the control system is relatively complicated.

To address the problem of frequent instrument interchanges in laparoscopic procedures, multitasking tool platforms have become an important research area. In Refs. [15] and [16], a NOTES robot with an end effector carrying multiple tool tips guided by a steerable and shape lockable drive mechanism was presented.

However, manipulation was limited by the lack of multiple curvature sections in the underactuated cable-driven system. Moreover, the accuracy was hampered by the nonlinear cable displacement.

Based on our previous work [15,16], this paper presents a novel ADM containing two independent curvature sections for a bimanual, multifunctional NOTES manipulator. The ADM consists of an articulated snakelike linkage, motor housing, and an arm connector. The snakelike linkage can articulate into complicated “S” shapes, better matching the tissue geometry and reducing the support force needed from the natural lumen. A novel connector between the bimanual arms and the ADM makes the system reconfigurable to change between insertion/removal and active surgical states. A linear cable actuation is used to orient the ADM. In Ref. [17], some parts of this ADM were briefly described. This paper presents the details of the whole design, as well as analysis of workspace and cable displacement. Experimental results give preliminary validation of the feasibility and capability of the ADM system.

2 Methods and Materials

The ultimate goal for this project is to design a dexterous bimanual transvaginal NOTES robot with a multifunctional manipulator on each arm to realize a cholecystectomy surgery. Each bimanual arm has 4DOF actuated by four on-board miniature DC motors to achieve full dexterity. Each multifunctional manipulator contains three tool tips for tool changing in the surgical field. An ADM, consisting of an articulated snakelike linkage, motor housing, and an arm connector, is used to orient the arms to the expected position and provides support for the manipulators to complete the surgery as shown in Fig. 1. A Phantom Omni joystick is used as a master manipulator and the controller is implemented in LABVIEW. The ADM faces several challenges, including providing versatile positioning, minimizing reaction force from the natural orifice structure, shape locking and reconfiguration methods to connect and disconnect with the central arm. This paper will focus on the design of the ADM and addressing these challenges.

2.1 Robot Arm Connector. To complete the surgery, the bimanual robot and the ADM have to be inserted from outside the body to reach the peritoneal cavity through the natural orifice. After the surgery, the surgical device needs to be similarly removed. In Ref. [18], an interesting way of folding such a robot was shown. Figure 2 illustrates the robot operation sequences of this method.

Fig. 2 (a) Insertion configuration and (b) removal configuration

Table 1 Cable connection states for insertion/removal

Step	Body-connected cable state	Arm-connected cable state
Insertion		
1	Slackened	Tensioned
2	Tensioned	Slackened
3	Tensioned	Slackened
Removal		
1	Slackened	Slackened
2	Slackened	Tensioned
3	Slackened	Tensioned

Insertion

- The two arms are unfolded and inserted, followed by the ADM (shown as step 1 in Fig. 2(a)).
- The two arms fold to their deployed position; both the arm-connected cable and body-connected cable are slackened (shown as step 2 in Fig. 2(a)).
- The arm-connected cable remains slackened, while the body-connected cable is tensioned until the central arm connects with the ADM (step 3 in Fig. 2(a)).

Removal

- The body-connected cable is slackened, and the ADM is pulled out slightly (shown as step 1 in Fig. 2(b)).
- The arm-connected cable is pulled until the end of the body-connected cable touches the ADM, and the arm is unfolded (shown as step 2 in Fig. 2(b)).
- When the arms are unfolded, the whole system can be removed (shown as step 3 in Fig. 2(b)).

Table 1 lists the states of the two connected cables, which characterize the operation sequence.

During the insertion and removal, the operator alternates the master manipulator between operating the bimanual arm and controlling the ADM by pushing a switch button on the control panel. Therefore, successful insertion/removal is realized by adjusting the shape of the ADM and bimanual arm in a coordinated fashion to fit in the compact workspace.

The connector should not only firmly connect the robotic arm with the ADM during surgery but also provide an easy way to assemble and disassemble the two. This challenge is resolved as follows.

As shown in Fig. 3, the connector attaches the central link of the bimanual manipulator with the snakelike linkage.

As shown in Fig. 4, there is a conical docking clamp in the middle of the center link of the bimanual manipulator. A hole, containing a small spring, is coaxial with the cone. The body-

Fig. 3 Prototype of the connector **Fig. 4 Details of the connector**

connected cable, used to connect the robotic arm and the ADM, passes through the hole and is fixed with the center link outside the hole. This cable also passes through the connector and the snakelike linkage and emerges in the external control unit. The conical docking clamp has 12 internal spline teeth which mate with external teeth on the connector to prevent relative rotational movement between the two when they are connected. To prevent translational movement, there are two small sliders on the conical surface of the connector arranged symmetrically. Attached to the sliders is a U-shaped Nitinol wire which is guided by the trigger cable. When the trigger cable is pulled, the Nitinol wire is forced to fold slightly and drive the sliders to move radially inward. Once the cable is released, the shape memory of the Nitinol wire assists the return of the sliders. The sliders prevent translational movement when they are engaged with the groove in the cone of the center link of the manipulator. The trigger cable shares the same channel with the body-connected cable. To disassemble the system, it is sufficient to tension the trigger cable again; the slider retracts and the force in the spring causes the connector to release from the manipulator. There is another circular groove in the middle of the connector which acts as a terminator to fix the actuation cables for the snakelike linkage. At the bottom of the connector, a clevis connects with the snakelike linkage.

2.2 Snakelike Linkage. As shown in Fig. 5, the snakelike linkage is composed of a straight section and 15 linkage pieces articulated serially. The purpose of the straight section is to match a relatively straight section of entry lumen it traverses. The straight part also plays a role in connecting the linkage pieces with the motor housing.

As shown in Fig. 6, each of the linkage pieces is arranged for participation in two rotational DOF (pitch and yaw) about two orthogonal axes. Each link of the five distal linkage pieces and the five proximal linkage pieces are capable of rotating ± 20 deg with respect to adjacent links, while the middle five linkage pieces rotate ± 30 deg with respect to adjacent links. This design feature is to meet the requirement of different curvature in the middle section compared to the rest of the access lumen; this allows retroflexion of the robot to approach certain surgical targets in the abdominal cavity when approaching from a transvaginal incision. One shorter clevis on the top and one wider clevis at the bottom provide the engagement to articulate the linkage pieces. Each link is 15.23 mm in length and 15.88 mm in diameter. Two holes traverse each linkage piece to lighten the weight. A channel through the central axis of each link is used for the actuation cables for the connector to pass through.

Fig. 5 Snakelike linkage

Fig. 6 (a) Single link and (b) two links of the distal section

Eight cables divided into two groups are used to actuate the ADM, which operates as two independent curvature sections as shown in Fig. 7. The first cable group, including two pairs of opposing cables, traverses the straight link and the first eight linkage pieces, while the second group, including another two pairs of opposing cables, passes through the whole ADM and attaches on the arm connector at the distal end of the ADM. The cables are made of nylon monofilament and carry up to 220 N of tension. In

Fig. 7 Cable distribution in the snakelike linkage

Fig. 8 Motor housing design

Fig. 9 Illustration of motor housing

each group, the pairs of opposing cables are controlled by a single motor in the motor housing.

2.3 Motor Housing. As shown in Fig. 8, the motor housing has two similar compartments connected serially, each containing two motors. The cables are fixed on the attachments which are mounted with the lead nuts. The motors in the first compartment actuate the first group of four cables. The motors in the second compartment actuate another group of four cables. Each motor actuates a pair of opposing cables.

To illustrate how the motor housing works, one opposing pair of lead screws is taken as an example, as shown in Fig. 9. As the motor rotates counterclockwise, lead screw 1 rotates clockwise. Due to the four gears, lead screw 2, which is in the diagonal position, rotates counterclockwise. As the two lead screws rotate in opposing directions, the two screw nuts will move in opposing directions. Therefore, the two cables fixed on the attachments move in opposing directions. All the pairs of opposing cables are controlled in this way.

3 Calculations and Analysis

3.1 Workspace. As the ADM is redundant and underactuated, it is impossible to determine the exact position of the end of the ADM. However, as the linkage pieces with common DOF

Fig. 10 Reference frames of DH convention

Table 2 DH parameters

i	a_{i-1}	α_{i-1}	d_i	θ_i
1	90 deg	l_s	0	θ_1
2, 4, 6, 8	-90 deg	l_p	0	θ_2
3, 5, 7	90 deg	l_p	0	θ_1
10, 12, 14, 16	-90 deg	l_p	0	θ_9
9, 11, 13, 15	-90 deg	l_p	0	θ_{10}

rotation (yaw or pitch) are coupled together by the same cables, we may make constraint assumptions based on this coupling. Here it was assumed that in each curvature section the distributions of pitch and yaw angular displacements were uniform. Furthermore, to strengthen the coupling and make this assumption reliable, a Nitinol wire with 1.5 mm diameter is installed in the center of the snakelike linkage as a stiffening backbone.

Using the Denavit–Hartenberg (DH) convention, the reference frames are placed on the ADM as shown in Fig. 10. The frames with the same color have the same rotation type, either yaw or pitch.

Table 2 shows the DH parameters. a_{i-1} is 15.23 mm which is the length of the linkage pieces, except for a_0 (138.4 mm, the length of the straight section). θ_i is the rotation of frame i around θ_i . Based on the assumption, $\theta_1 = \theta_3 = \theta_5 = \theta_7$, $\theta_2 = \theta_4 = \theta_6 = \theta_8$, $\theta_9 = \theta_{11} = \theta_{13} = \theta_{15}$, and $\theta_{10} = \theta_{12} = \theta_{14} = \theta_{16}$. All the angle variables have the same rotation range from -20 to 20 deg.

By using the DH convention, the resulting workspace is shown in Fig. 11. Extreme poses, some illustrative of workspace boundaries, are shown in Fig. 12. The workspace covers a volume of approximately $2.4L$, which overlaps about 90% of the human peritoneal cavity as shown in Ref. [16]. Adding the workspace of the bimanual arm (not analyzed in this paper), the workspace is expected to be sufficient for the ADM to properly locate the robot for any typical surgical work.

Fig. 11 Workspace

Fig. 12 Extreme poses

3.2 Cable Displacement. There are four active DOF for this ADM. Therefore, the calculation of the cable displacement should be based on these four DOF (θ_1 , θ_2 , θ_9 , and θ_{10}).

Figure 13 shows two linkage pieces which rotate a certain angle θ about the axis from an initial straight position. According to the geometry, the original gap length between adjacent links, which is spanned by cable 1 (C_1), is S , and the length after the rotation is S' .

$$S = 2l \sin 10 \text{ deg} \quad (1)$$

$$S' = 2l \sin \left(\frac{20 \text{ deg} + \theta}{2} \right) \quad (2)$$

Fig. 13 Schematic diagram for cable displacement

where l is the distance between the center of the actuation cable hole and the relative rotation axis, as shown in Fig. 13.

Therefore, the displacement of C_1 , ΔS is the difference between S and S' .

$$\Delta S = 2l \sin\left(\frac{20 \text{ deg} + \theta}{2}\right) - 2l \sin 10 \text{ deg} \quad (3)$$

This calculation method can be applied for the overall displacement calculation. For the first curvature section, if the pitch angle rotates θ_1 , and yaw angle rotates θ_2 , the displacements (d_{1-4}) are as follows:

$$d_1 = -8l_1 \left[\sin 10 \text{ deg} - \sin\left(\frac{20 \text{ deg} - \theta_1}{2}\right) \right] - 8l_2 \left[\sin 10 \text{ deg} - \sin\left(\frac{20 \text{ deg} - \theta_2}{2}\right) \right] \quad (4)$$

$$d_2 = -8l_1 \left[\sin 10 \text{ deg} - \sin\left(\frac{20 \text{ deg} - \theta_1}{2}\right) \right] + 8l_2 \left[\sin\left(\frac{20 \text{ deg} + \theta_2}{2}\right) - \sin 10 \text{ deg} \right] \quad (5)$$

$$d_3 = -8l_1 \left[\sin\left(\frac{20 \text{ deg} + \theta_1}{2}\right) - \sin 10 \text{ deg} \right] - 8l_2 \left[\sin\left(\frac{20 \text{ deg} + \theta_2}{2}\right) - \sin 10 \text{ deg} \right] \quad (6)$$

$$d_4 = -8l_1 \left[\sin\left(\frac{20 \text{ deg} + \theta_1}{2}\right) - \sin 10 \text{ deg} \right] - 8l_2 \left[\sin 10 \text{ deg} - \sin\left(\frac{20 \text{ deg} - \theta_2}{2}\right) \right] \quad (7)$$

where l_1 (5.39 mm) is the distance between the center of the actuation cable hole and the pitch axis; l_2 (3.93 mm) is the distance between the center of the actuation cable hole and the yaw axis in the first curvature section.

For the second curvature section, the displacement of the cables should first follow the displacement of the related cables in the first curvature section, and then move according to their own pitch and yaw angles (θ_{9-10}). Therefore we can obtain the displacement as follows:

$$d_5 = d_1 - 8l_2 \left[\sin 10 \text{ deg} - \sin\left(\frac{20 \text{ deg} - \theta_9}{2}\right) \right] - 8l_1 \left[\sin 10 \text{ deg} - \sin\left(\frac{20 \text{ deg} - \theta_{10}}{2}\right) \right] \quad (8)$$

$$d_6 = d_2 - 8l_2 \left[\sin 10 \text{ deg} - \sin\left(\frac{20 \text{ deg} - \theta_9}{2}\right) \right] + 8l_1 \left[\sin\left(\frac{20 \text{ deg} + \theta_{10}}{2}\right) - \sin 10 \text{ deg} \right] \quad (9)$$

$$d_7 = d_3 + 8l_2 \left[\sin\left(\frac{20 \text{ deg} + \theta_9}{2}\right) - \sin 10 \text{ deg} \right] - 8l_1 \left[\sin\left(\frac{20 \text{ deg} + \theta_{10}}{2}\right) - \sin 10 \text{ deg} \right] \quad (10)$$

$$d_8 = d_4 + 8l_2 \left[\sin\left(\frac{20 \text{ deg} + \theta_9}{2}\right) - \sin 10 \text{ deg} \right] - 8l_1 \left[\sin 10 \text{ deg} - \sin\left(\frac{20 \text{ deg} + \theta_{10}}{2}\right) \right] \quad (11)$$

Fig. 14 Error versus joint variable

With these kinematic equations, the displacement of the cables can be controlled, and ultimately the position of the manipulator at the end of the ADM can be prescribed.

Each pair of opposing cables is controlled by the same motor in this design, which means that each pair of opposing cables has the same displacement but opposite direction, so we assume that $d_1 = -d_3$, $d_2 = -d_4$, $d_5 = -d_7$, $d_6 = -d_8$. However, there is some difference between the displacements of each opposing pair of cables, which may weaken this assumption and make the cables stretch or slacken during operation. Therefore, the error between corresponding opposing cables should be analyzed. As all pairs of opposing cables in each curvature section follow similar relationships, a single analysis is presented. For instance, error = $d_5 - (-d_7)$.

As we can see in Fig. 14, the maximal displacement error is 0.8 mm. Using cable kinematic equations, the maximal displacement can be obtained as 51.11 mm. So the maximal relative error is 1.54%, which is acceptable considering the cable material properties (maximum elongation). Therefore, the motor arrangement is reasonable, especially considering the surgeon-in-the-loop nature of control based on camera feedback.

4 Experiments and Results

Three kinds of experiments were conducted to verify the performance of the ADM in order to direct further modification and improvement. The experiment setup is shown in Fig. 15. A computer with LABVIEW software was used as the control system, with a CompactRIO device driving four Faulhaber 2232 motors.

4.1 “S” Shape. In snakelike surgical robots with one curvature section, for instance [19], 90-deg orientation is considered good dexterity. Therefore, for the presented snakelike drive

Fig. 15 Benchtop testing setup

Fig. 16 (a) “S” shape in the horizontal plane and (b) “S” shape in the vertical plane

Fig. 17 (a) Target reaching in horizontal plane and (b) target reaching in vertical plane

mechanism with two curvature sections, the ability to achieve an “S” shape in both horizontal and vertical planes can be considered a benchmark toward verifying that the ADM has the capacity to provide sufficient orientation during surgery. Therefore, one experiment was conducted to drive the ADM to articulate an “S” shape in the two planes.

The results are shown in Fig. 16. The ADM achieved an “S” shape in both planes. In both horizontal and vertical planes, the first section rotated 90 deg and the second section also rotated 90 deg.

4.2 Reaching Expected Targets. In order to validate the cable kinematics, two points in the coverage of the workspace

were chosen as the targets for the end of the ADM to reach. One target is in the horizontal plane and the other one is in the vertical plane, as shown in Fig. 17. The locus of the linkage predicted by the cable kinematic model is shown for comparison.

As can be seen in Fig. 17, in both planes, the articulated links follow the theoretical cable kinematics to reach the targets with minor error. The errors at the distal end of the ADM are less than 5 mm in the horizontal plane and less than 8 mm in the vertical plane as shown in Fig. 17. This minor error may be due to the accuracy of the cable fixation and/or other workmanship issues. This operational difference is not significant enough to affect surgery, particularly since in surgical practice, vision feedback is used to compensate for these kinds of positioning differences.

4.3 Assembly and Disassembly of the Connector. According to the design concept described in Sec. 2.1, the cable was pulled to connect the end effector with the ADM. Tensile force was measured to check whether the components were connected firmly. Then another cable was pulled to disconnect the components. The experiment was repeated eight times, and successful connection and disconnection was achieved five times. The three instances of failure were due to excessive friction between the sliders and surface of the guideway, preventing the sliders from retracting as the cable is released; this is a target for future design improvement through better workmanship during prototyping. The largest measured tensile connection force was 20 N (2.12 kg, as shown in Fig. 18), which is adequate to support surgically relevant loads considering the force data in Ref. [20].

5 Conclusions

In this paper, a novel ADM was designed for a bimanual, multi-functional NOTES manipulator. The ADM contains two independent curvature sections. The experiments demonstrated that it could meet the requirement to achieve an “S” shape and verified that it has the capacity to provide sufficient orientation workspace

Fig.18 Connecting force measurement

for NOTES. In addition, the ADM has a large position workspace. Target reaching experiments verified the correctness of the cable displacement kinematics. A novel connector design provides a convenient and efficient way to assemble and disassemble the system for insertion/removal. Future work involves improving the cable routing, optimizing the control system, integrating the ADM with the multifunctional manipulator and performing validation experiments in animal models.

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