Design, control and testing of a novel compact laparoscopic endoscope manipulator

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Abstract: This paper describes the development of a compact laparoscopic endoscope manipulator and its command interface for use as a surgical assistant during minimally invasive surgery. The defining feature of the endoscope manipulator is that it is sufficiently small and lightweight to be fixed directly on the abdomen of the patient. The mechanism of the manipulator controls the orientation of the endoscope and its insertion depth. It is actuated by cables inside flexible sleeves connected to a separate enclosure containing analogue controllers, servomotors and rack-and-pinion drives. Compared with floor-standing endoscope manipulators, the described device is easier to set up, cheaper, simpler and allows unrestricted access to the abdomen from all sides of the patient. The pointing accuracy of the device is reduced by the absence of a rigid base, but the resulting compliance to patient motion is an added benefit. The current prototype has been tested on a cadaver. The design and control of the endoscope manipulator continues to evolve in response to testing results and consultation with surgeons, with light weight, small size, simplicity and ease of use as primary considerations. A novel hands-free user control interface for orientation of the endoscope manipulator using an external optical localizer to track surgical instruments is also presented.

Keywords: surgical robotics, laparoscopy

NOTATION

$\boldsymbol{A}$	surgical instrument tip position
$\boldsymbol{B}$	endoscope tip position
$\boldsymbol{B}_1, \boldsymbol{B}_2, \boldsymbol{B}_3, \boldsymbol{B}_4$	sleeve end positions
$F_p(l)$	cubic polynomial fit to a set of measured pressure to length data for a given McKibben muscle
K	proportional error feedback gain
l	McKibben muscle length
l_d	desired muscle length
l_r	sensed muscle length
l_1, l_2, l_3, l_4	extended actuator cable lengths of the first prototype
$\boldsymbol{O}$	incision position and coordinate frame origin
P	McKibben muscle internal pressure
$\mathbf{R}$	rotation matrix for endoscope orientation
$\boldsymbol{T}_1, \boldsymbol{T}_2, \boldsymbol{T}_3, \boldsymbol{T}_4$	cable end positions
x, y, z	Cartesian coordinates
θ	spherical coordinate and endoscope rotation
ρ	spherical coordinate and endoscope extension
ϕ	spherical coordinate and endoscope inclination

1 INTRODUCTION

Minimally invasive surgical procedures on the abdomen are performed using long, thin instruments through multiple 10 mm keyhole incisions with the abdomen inflated to a given pressure. Rigid endoscopes are necessary to display internal organ tissues and instruments on a video monitor because the surgeon performing the procedure cannot see directly inside the patient. The endoscope must generally be held and moved to various orientations and insertion depths to observe different areas of interest in the abdomen during a procedure. The endoscope moves inside a trocar tube which is placed in the incision.

As the surgeon generally holds an instrument in each hand during the procedure, an assistant is needed to hold the endoscope in the desired positions and orientations. This task is fairly straightforward and well defined yet

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awkward and tiring for a human assistant; rather than occupying an additional trained professional assistant during the procedure, it is worthwhile using a robotic device as a surgical assistant to hold and move the endoscope instead.

1.1 Previous endoscope manipulators

Other robots for laparoscopic endoscope manipulation are described in references [**1**] to [**3**]. The kinematics of endoscope robots may be designed to take advantage of the fixed insertion point of the endoscope incision to place a remote centre at the endoscope incision point [**4**]. The AESOP [**5, 6**] endoscope manipulator from Computer Motion, Inc. and the EndoAssist [**7**] from Armstrong Healthcare are both commercially available devices. ZEUS from Computer Motion and DaVinci [**8**] from Intuitive Surgical Systems are complete minimally invasive robotic surgical systems teleoperated by a surgeon from a master console.

Preliminary clinical studies have indicated that the use of AESOP and other endoscope manipulators does not significantly affect the safety or efficacy of various minimally invasive surgical procedures [**9–11**]. Furthermore, image stability was improved by using endoscope manipulators, and in some cases the completion times of procedures were reduced [**7**].

2 PRELIMINARY COMPACT ENDOSCOPE MANIPULATOR DEVELOPMENT

For practical use in an operating room environment, the endoscope manipulator must be unobtrusive, safe, simple to set up and use and easily sterilizable. To meet these needs, the objective has been a design that is small, lightweight and fixed to the patient. The use of cables inside flexible sleeves (Bowden cables) to operate the robot allows the actuators to be placed away from the actual positioning mechanism. The use of cable actuation for positioning of an endoscope robot on the abdomen was inspired by an existing tele-echography robot in the present authors' laboratory [**12**], developed to enable remote performance of ultrasound examinations and originally proposed by Cinquin and Troccaz [**13**].

Because the endoscope typically does not contact internal tissues during surgical interventions, safety concerns are not as critical as they would be for manipulation of cutting and grasping instruments. Nevertheless, the compact endoscope manipulator design is intrinsically safer than large floor-standing ensdoscope manipulators for two reasons:

1. The actuators in the compact design are much less powerful than those required for a large robot arm, so they are incapable of causing large forces on the patient inadvertently.
2. Unforeseen motions of the patient are much less likely to cause increased contact forces of the endoscope at the incision point because the compact manipulator is placed directly on the abdomen.

Since the insertion point of the endoscope is invariant, three degrees of freedom (DOF) are sufficient to move the endoscope to all possible configurations, with two rotational DOF to determine the endoscope direction and one translational DOF for the insertion depth. A fourth DOF could be implemented in addition to rotate the endoscope about its own axis, but for a straight-view endoscope this rotation is equivalent to a rotation of the video image.

2.1 Functional requirements

The three DOF that must be controlled by an endoscope manipulator during surgery are shown in Fig. 1: the insertion depth of the endoscope into the incision is determined by the extension, ρ, the inclination, ϕ, is the angle between the endoscope shaft and the vertical, and the rotation angle, θ, is the orientation of the shaft in the horizontal plane, with both angles relative to the pivot point of the endoscope incision. These three DOF enable the surgeon to view any point in the abdominal cavity at any desired distance.

The actuators of the endoscope robot must be capable of supporting and moving a maximum 300 g camera at an extension of 300 mm, producing a torque load of 0.88 N m at the pivot point. The required range of motion for an endoscope manipulator depends on the procedure to be performed; in practice, the aim has been full 360° rotation in the horizontal plane with as much inclination as practicable and a range of at least 200 mm in translation.

Absolute accuracy and speed are less critical in this application than for typical industrial robots. It is sufficient to be able to move between any two configurations of the robot within several seconds. Positioning repeatability to within several millimetres is also sufficient.

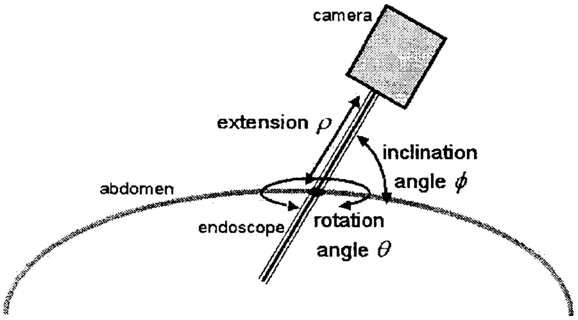

Fig. 1 Compact endoscope manipulator requirements

2.2 First prototype

The first compact endoscope manipulator prototype is pictured in Fig. 2 and schematically in Fig. 3. It is described in detail in reference [**14**]. This prototype uses four cable actuators in parallel to control the endoscope orientation and a single cable actuator opposing compression springs along the endoscope shaft to control insertion depth. McKibben pneumatic artificial muscle actuators [**15**, **16**] were initially chosen owing to their simplicity and the passive compliance and damping that they provide. Considerable development and analysis of McKibben actuators have been performed by Tondu and Lopez [**17**] and by Chou and Hannaford [**18**]. McKibben artificial muscles consist of a rubber tube covered with a braided sheath and attached to an air pressure source, as pictured in Fig. 4. Added pressure causes the rubber tube to shorten and generates a tensile force between the ends of the actuator owing to the warping of the braided sheath, but this relationship is non-linear.

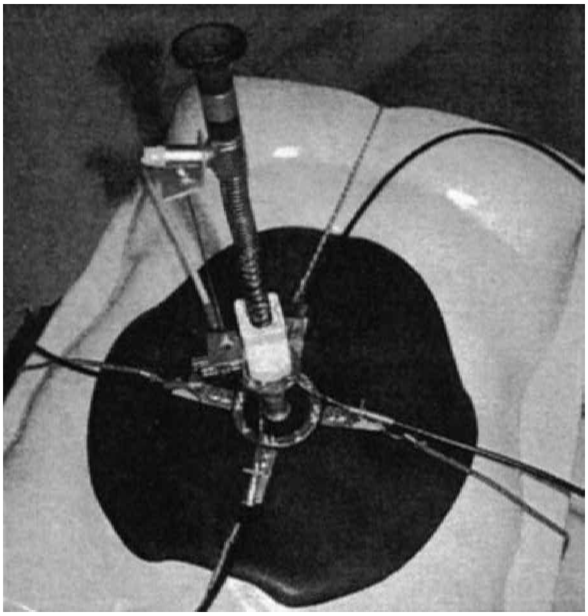

Fig. 2 First compact endoscope robot prototype

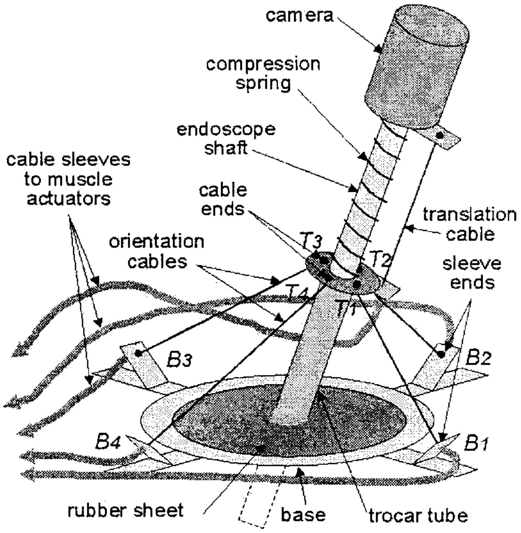

Fig. 3 Schematic of first compact endoscope robot prototype

If the curvature of the cables between the sleeve ends and the endoscope is neglected, then the four cable lengths, l_n, can be calculated from the positions of the cable ends, $\boldsymbol{T}_n$, and the ends of the cable sleeves, $\boldsymbol{B}_n$, with $n = 1, 2, 3, 4$, as

$$l_n = |\boldsymbol{B}_n - \boldsymbol{T}_n| \tag{1}$$

The locations of the cable ends, $\boldsymbol{T}_n$, are given by the rotation matrix $\mathbf{R}$ describing the orientation of the endoscope and the locations of the cable end fittings, $\boldsymbol{T}_n^{\mathrm{e}}$, relative to the incision point in the coordinate system fixed to the endoscope:

$$\boldsymbol{T}_n = \mathbf{R}\boldsymbol{T}_n^{\mathrm{e}} \tag{2}$$

2.3 First prototype control

Open-loop control and feedback controllers were implemented. The first controller is open loop in that only the pressure in the pneumatic muscles is sensed during operation and the desired pressure is calculated from the cable lengths necessary to support the endoscope in a given orientation. The relationship between pressure and cable length for each actuator is determined by a cubic polynomial curve fit to calibration data. The second control method uses PT1A cable-extension position transducers from Celesco Transducer Products, Inc., attached to the pneumatic artificial muscles to measure the lengths of the cables used to manipulate the endoscope during operation.

Figures 5 and 6 show the endoscope orientation open-loop and feedback control response while the endoscope is extended, with the motion of the endoscope camera recorded by a POLARIS optical position localizer from Northern Digital, Inc. For each plot, a step command was issued to move the manipulator from its initial position to one on the opposite side of its motion range, followed by a second step command to return to the initial position. On account of the damping in the muscle actuators used and the friction in the cables, satisfactory proportional, integral and derivative (PID) error gain controller performance was achieved with the integral and derivative feedback gains set to zero, resulting in the feedback control law

$$P = F_{\mathrm{p}}(l_{\mathrm{d}}) + K(l_{\mathrm{r}} - l_{\mathrm{d}}) \tag{3}$$

where P is the pressure command sent to the pneumatic muscle valve, $F_{\mathrm{p}}(l)$ is a cubic polynomial fit to a set of measured pressure to length data for a given McKibben muscle, l_{d} is the desired muscle length, K is the proportional error feedback gain and l_{r} is the sensed muscle length. The feedback controller shows improvements

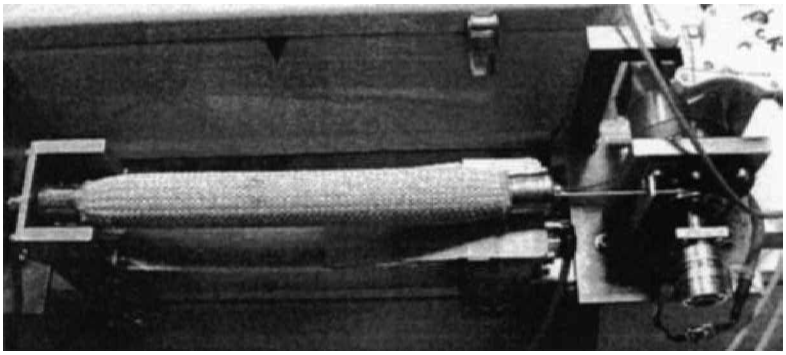

Fig. 4 McKibben pneumatic artificial muscle

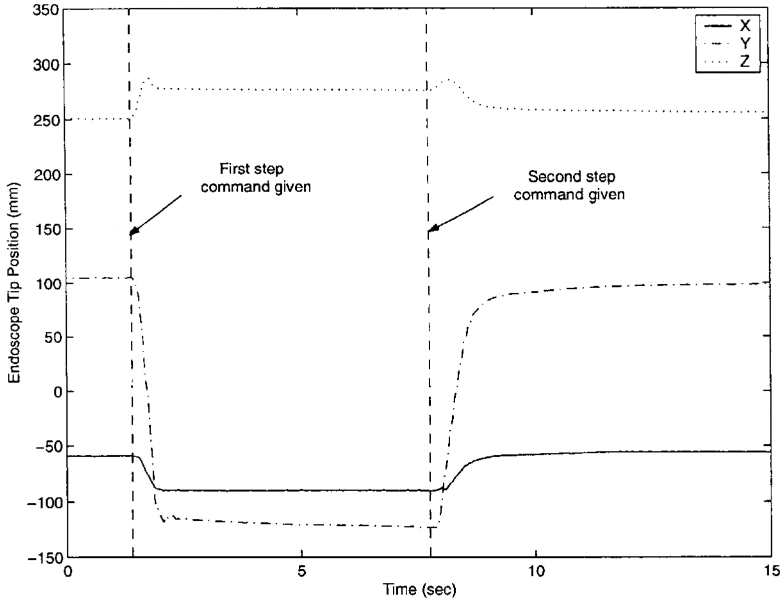

Fig. 5 Open-loop endoscope orientation control

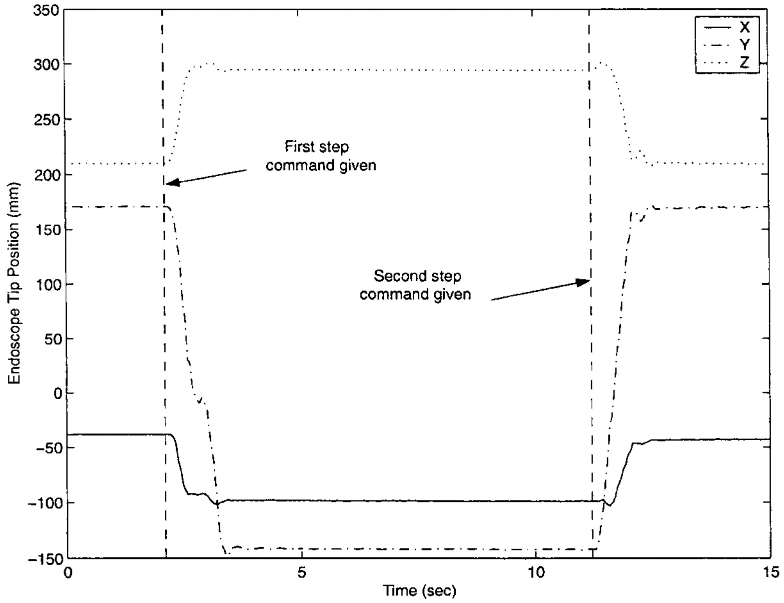

Fig. 6 Feedforward and PID endoscope orientation control

in settling time and repeatability as compared with the open-loop controller, although some oscillation remains in the settling period after the step commands.

3 CURRENT PROTOTYPE

Owing to shortcomings in the first prototype to be described in the following sections, a second prototype was fabricated which is in use currently. The current prototype is pictured in Fig. 7 with a schematic model in Fig. 8. It is also described in reference [**19**].

3.1 Modifications from the first prototype

The current endoscope manipulator prototype retains the overall dimensions and cable-driven operation of the first prototype, but the actuators, controller and positioning mechanism have been changed to render the device simpler, easier to control, more reliable and more accurate. The artificial pneumatic muscles of the first prototype were difficult to control smoothly owing to their non-linearity and delayed response and often failed because of rupture of the internal rubber tubing. These actuators were replaced by gearmotors with rack-and-pinion drives to pull the cables to the mechanism, shown in Fig. 9. The motors are controlled by analogue servocontrollers instead of a digital PID controller. The motors, drives, power supply and controllers are contained in a single enclosure.

The configuration of four separately actuated cables operating in parallel to control the orientation produces a vertical force on the trocar and abdomen which must be balanced by the elasticity of the rubber sheet at the base of the first prototype. Furthermore, inclination of the endoscope close to the horizontal plane of the abdomen caused the cables to bend with a very small radius of curvature, which produced permanent deformations, wear and residual stresses in the cables. To resolve these problems, simplify the kinematics of the device and reduce the required number of actuators, the orientation mechanism was replaced by a rigid device with two rotational joints, pictured in Fig. 7.

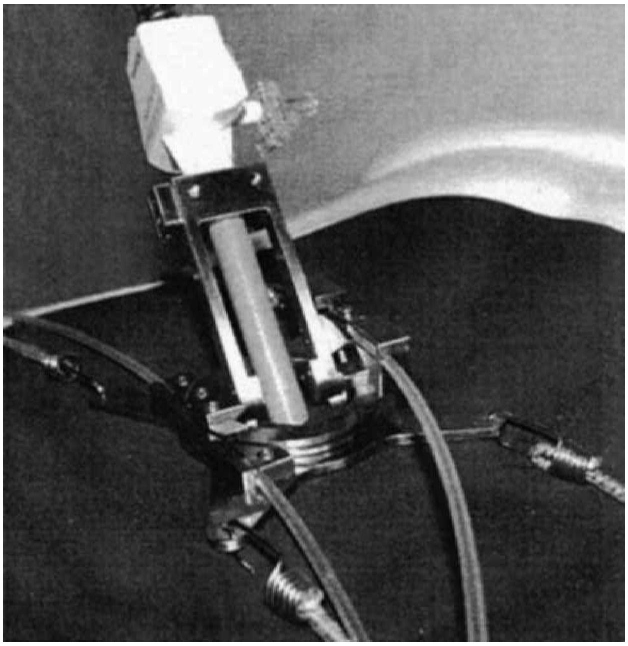

Fig. 7 Laparoscopic endoscope manipulator on simulation abdomen

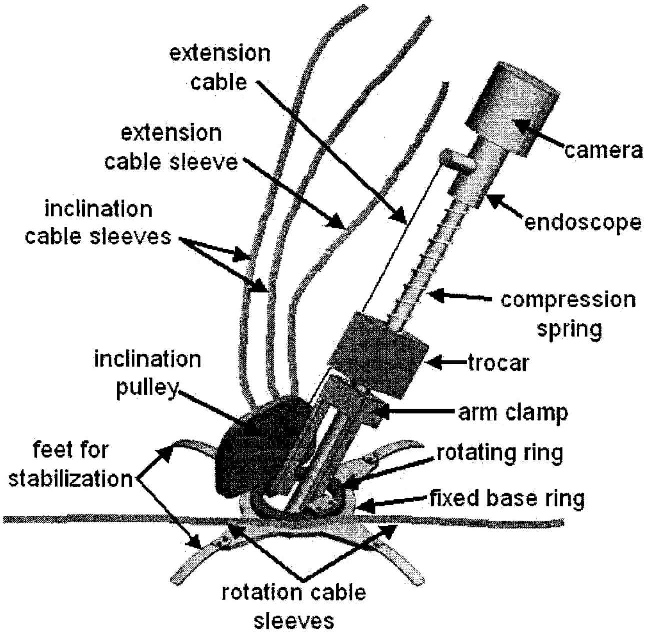

Fig. 8 Current prototype schematic

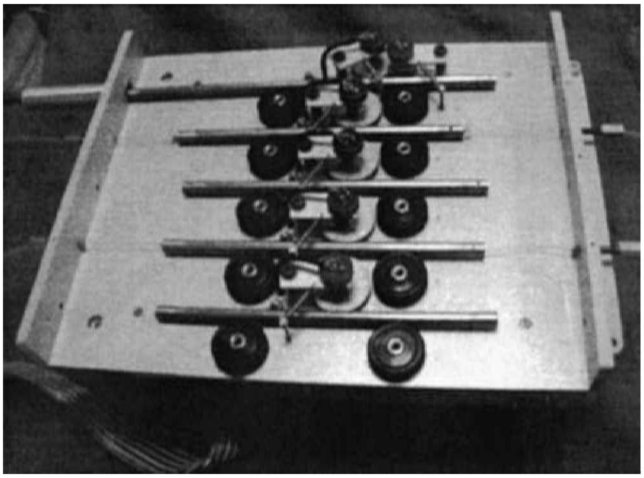

Fig. 9 Actuator motors and drives

3.2 Current mechanism

The mechanism of the new prototype consists of a round base, a clamp to hold the endoscope trocar and two joints which enable azimuth rotation and inclination of the endoscope pivoting about the insertion point. The axes of the two rotation joints intersect at the endoscope insertion point incision.

Each rotational joint is driven by a single motor and rack and pinion with a cable attached at each end to rotate the joint in both directions. Endoscope translation is determined by a single cable opposed by a compression spring as in the previous prototype, actuated by a third motor and rack. Each motor is controlled in position by an analogue feedback servocontrol circuit. The new motorized actuation system is more compact, more easily controlled and more reliable than the previous pneumatic muscle actuators. The cables are replaceable and the tension is easily adjustable to compensate for stretching from repeated use.

The current endoscope orientation mechanism is more precise and more robust as there are no flexible components in the mechanism other than the actuation cables which drive the two rotational joints. Furthermore, there are no vertical forces on the endoscope at its insertion point. As the two cables that drive each rotation joint are in direct opposition and the sum of their lengths remains constant throughout the motion of the joint, the ends of the cables can be attached to opposite ends of a single rack and motor, so that only one motor is necessary for each DOF of the manipulator. For the same reasons, the kinematics and control of the new device are greatly simplified as well.

The mechanism is fabricated from stainless steel to be durable and easily sterilizable. The cables and sleeves are disposable and would be replaced before each surgical procedure for sterility. The endoscope insertion actuation cable can be released easily at any time to remove the endoscope from the trocar for replacement or cleaning of the lens.

3.3 Parameters

The relevant measured parameters of the current endoscope manipulator prototype are as follows:

Size	70 mm diameter, 75 mm height
Mass	350 g
Stiffness	0.6 N m/deg, 0.40 N/mm
Motion range	360° azimuth rotation, 60° inclination, 200 mm translation
Speed	75 deg/s, 80 mm/s

The given size and mass of the device do not include the length and mass of the endoscope and camera, which may be up to 450 mm and 340 g. The limited stiffness in rotation is due to the elasticity of the actuator cables, and that in translation is due to the compression springs opposing the cable on the endoscope shaft.

3.4 Experimental results

To confirm the performance of the current endoscope manipulator prototype, ramped motion trajectories were repeated in both directions for each DOF. During each commanded trajectory, the position of the endoscope viewpiece was recorded using a POLARIS optical localizer. These position coordinate data were converted to the manipulator actuation coordinates and are shown in Figs 10 to 12. These plots show settling times of less than 1 s and repeatability to better than 1° and 1 mm, although some unevenness is apparent on account of stiction, particularly during the θ rotation trajectory. Overall, the smoothness, accuracy and repeatability of the response of the device are more than sufficient for endoscope camera positioning in minimally invasive surgery, however.

The force to overcome friction in the Bowden cables varies in the range 2–5 N, depending on the cable tension and bending of the cable sleeves, provided that the minimum radius of curvature is greater than 100 mm. The cables used are polymer coated to minimize friction as well. As the cables stretch and wear after repeated use, they must be periodically retensioned and replaced. If the cables are maintained in moderate tension, hysteresis is minimized, although a few millimetres of hysteresis may typically remain in the actuators. Because the motion of the manipulator is generally under direct user control, absolute positioning inaccuracy due to hysteresis, cable stretch and the lack of calibration do not significantly affect the utility of the device.

4 USER COMMAND INTERFACES

Since the principal surgeon often has both hands occupied by surgical instruments while performing a surgical procedure, a hands-free operator interface for user control of the robot motion is preferable to a joystick or keypad which would require the surgeon to release an instrument to move the robot. A voice command recognition user control interface has been implemented, and it is planned to investigate the practicality of using small, wearable keypads to enable a surgeon to control the endoscope manipulator without releasing handheld instruments.

A novel user control interface that enables the endoscope manipulator automatically to centre the tip of a given instrument in the view of the endoscope camera through the use of an external optical position localizer has also been developed [**20**]. Although the use of an optical localizer adds complexity and cost to the present simple, low-cost endoscope manipulator, the complete system is still less costly and cumbersome than using a floor-standing robot to manipulate an endoscope. Furthermore, an optical localizer may already be available in an operating room where the endoscope

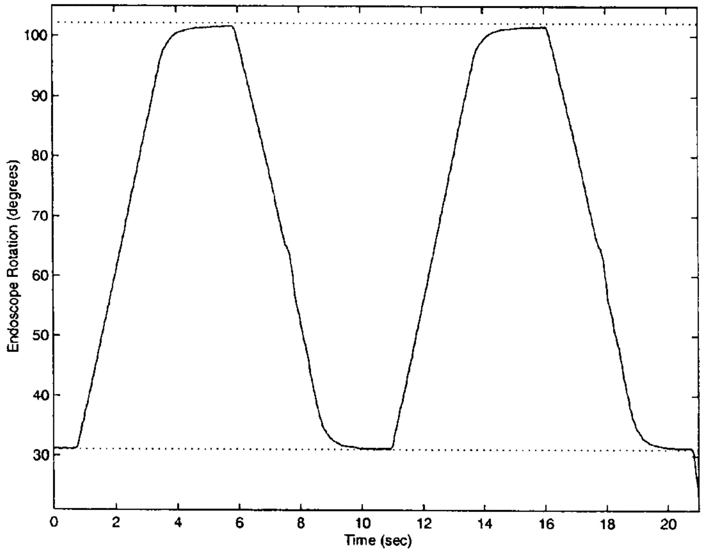

Fig. 10 Endoscope manipulator rotation trajectory response

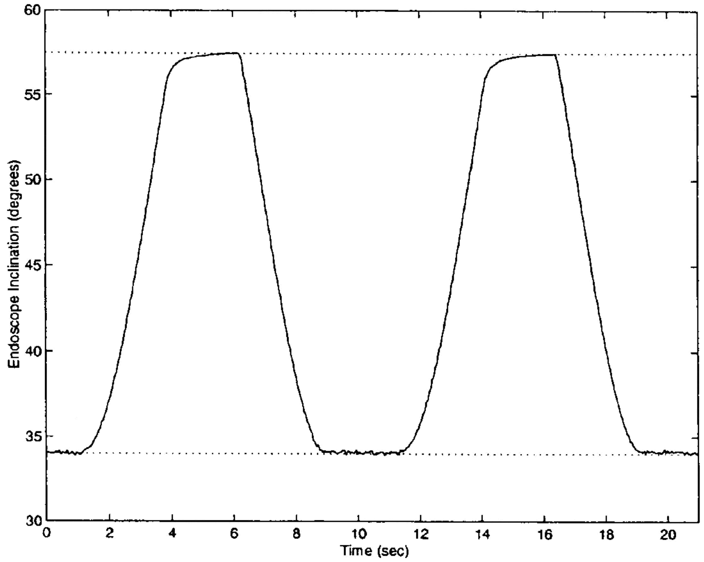

Fig. 11 Endoscope manipulator inclination trajectory response

manipulator is to be used, as they are useful in other computer aided surgical applications such as hip and knee alignment in joint replacement surgery.

Command interfaces that have been implemented for other endoscope manipulators include voice commands [**21**], eye [**22**] and head [**23**] motion tracking and miniature keypads attached to the hand or instrument which can be operated without releasing the instrument handle. Foot pedals are also a possible option as a command interface [**21**] but are not ideal because the three DOF of the robot must be controlled independently and foot pedals are often used to control other devices such as cutting and cautery instruments.

The aim is not to make claims as to the superiority of one user command interface over another for the endoscope manipulator, but rather to develop several different alternatives and allow surgeons to select a command interface for the present endoscope manipulator according to their own experience, preference and the type of surgery to be performed.

4.1 Position tracking

The developed control interface uses the motion of surgical instruments to generate position commands for the endoscope robot. If the motion of an instrument is tracked automatically, the robot can move to keep the tip of the instrument in the view of the endoscope camera, as shown in Fig. 13. In the present approach, use is made of a POLARIS optical localizer to detect the locations of the endoscope incision ***O***, the tip of a

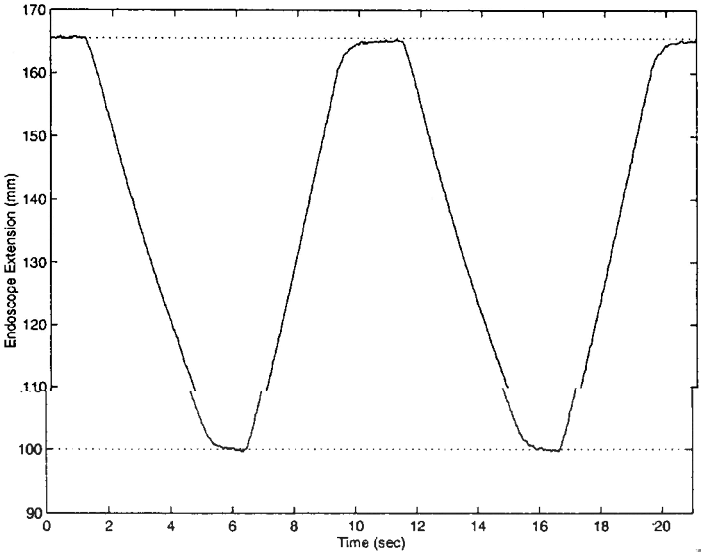

Fig. 12 Endoscope manipulator extension trajectory response

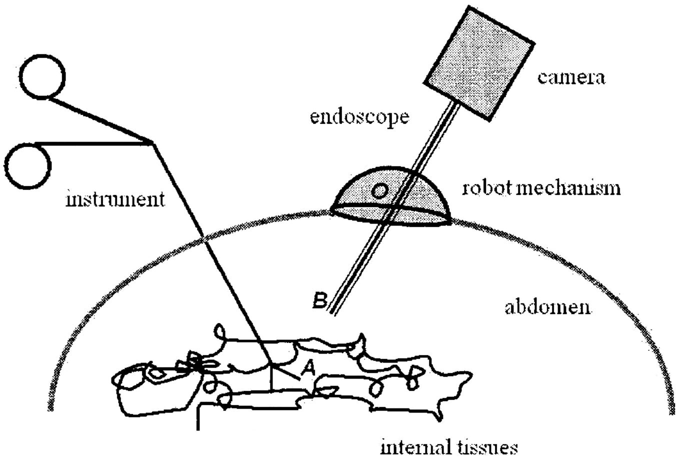

Fig. 13 Schematic of endoscope orientation during laparoscopic surgery

surgical instrument ***A*** and the tip of the endoscope ***B***. Although points ***A*** and ***B*** are inside the abdomen, their locations can be calculated from the positions and orientations of rigid-body position markers using multiple LEDs attached to the endoscope and the instrument outside the abdomen. Three rigid-body position markers are used: a stationary reference marker, a marker attached to the head of the endoscope and a marker attached to the handle of the surgical instrument for tracking.

To place the tip of the instrument at the centre of the endoscope video image, vectors ***A*** and ***B*** must have the same direction when the incision point ***O*** is defined as the origin, or

$$\boldsymbol{A} = c\boldsymbol{B} \tag{4}$$

where c is a scalar constant. In practice, position vector ***A*** is converted to spherical coordinates, and then the manipulator is commanded to move to the orientation angles corresponding to those coordinates.

The manipulator joint variables directly correspond to a spherical coordinate system with the origin located at the incision point of the endoscope, as shown in Fig. 14. Given the unit vector ***A***, it is possible to calculate the necessary θ rotation and ϕ inclination joint variables from the Cartesian x, y and z position variables given by the localizer as follows:

$$\rho = \sqrt{x^2 + y^2 + z^2} \tag{5}$$

$$\theta = \tan^{-1}(y/z) \tag{6}$$

$$\phi = \cos^{-1}\left(\frac{z}{\sqrt{x^2 + y^2 + z^2}}\right) \tag{7}$$

A joint motion command to move to the calculated θ and ϕ produces an endoscope view centred on the tip of the surgical instrument.

This control method requires the spherical coordinate reference frame of the robot joint variables and the Cartesian coordinate reference frame of the localizer to be registered to each other. This registration is typically

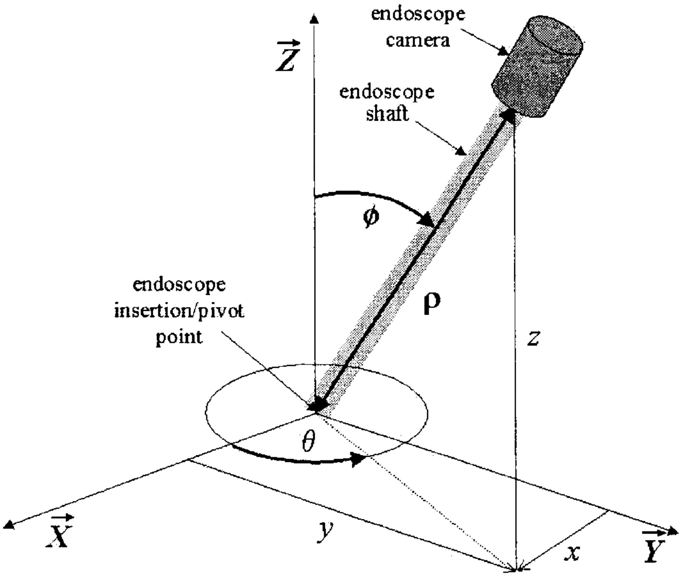

Fig. 14 Cartesian to spherical joint coordinates

done by moving the robot to different preset positions and detecting the locations of points on the robot with the localizer. These motions could be preprogrammed to be executed automatically as well, without modifying the calculations done to register the coordinate frames.

4.2 Automatically generated trajectory results

The described automatic instrument tracking endoscope position command interface has been successfully implemented on the present endoscope manipulator. Figure 15 displays the joint motion trajectories in degrees against time in seconds in response to a position command generated from the localizer data. The motion of the manipulator is smooth and requires only seconds to move between any two given endoscope configurations.

4.3 Alternative motion tracking methods

It would also be possible to implement an automatic instrument tracking system by using image processing methods to locate the tip of the instrument in the endoscope image and reorient the endoscope so as to centre on that point. The advantage of the localizer-based method compared with image processing methods is that the present method is not sensitive to changes in the appearance of the instrument tip on account of variable illumination. Since the detection of the endoscope and instrument tip locations is independent of the endoscope image, the instrument tip may be occluded or even completely out of the field of view of the endoscope, and the present instrument tracking method will still function correctly.

Another recent development is a simpler control interface method in which the motions of the instrument in the x and y directions of the localizer from a defined zero point directly command displacements in the θ and ϕ joint variables of the endoscope robot.

5 CADAVER TESTING AND FURTHER MODIFICATIONS

An initial test of the current endoscope manipulator prototype has been performed on a cadaver. The purpose of this preliminary test was to confirm the functionality of the mechanism and its control software on a human abdomen, to evaluate the ease of the device set-up and use in a clinical setting and to obtain comments from the attending surgeons for further modifications of the prototype. The set-up of the endoscope manipulator in place on the abdomen of the cadaver is shown in Figs 16 and 17.

The set-up of the endoscope manipulator did not pose any unforeseen difficulty, and the device successfully moved throughout its full design range of motion in all degrees of freedom. The endoscope incision was not airtight owing to diminished elasticity of the cadaver abdomen, which caused difficulty in inflating the abdomen properly. The comments from the surgeons present regarding the deficiencies of the endoscope robot prototype design are given below.

5.1 Comments from surgeons

The problems with the current prototype remarked upon by the surgeons in attendance were as follows:

1. The use of straps passing underneath the table to hold the base of the device in place on the abdomen

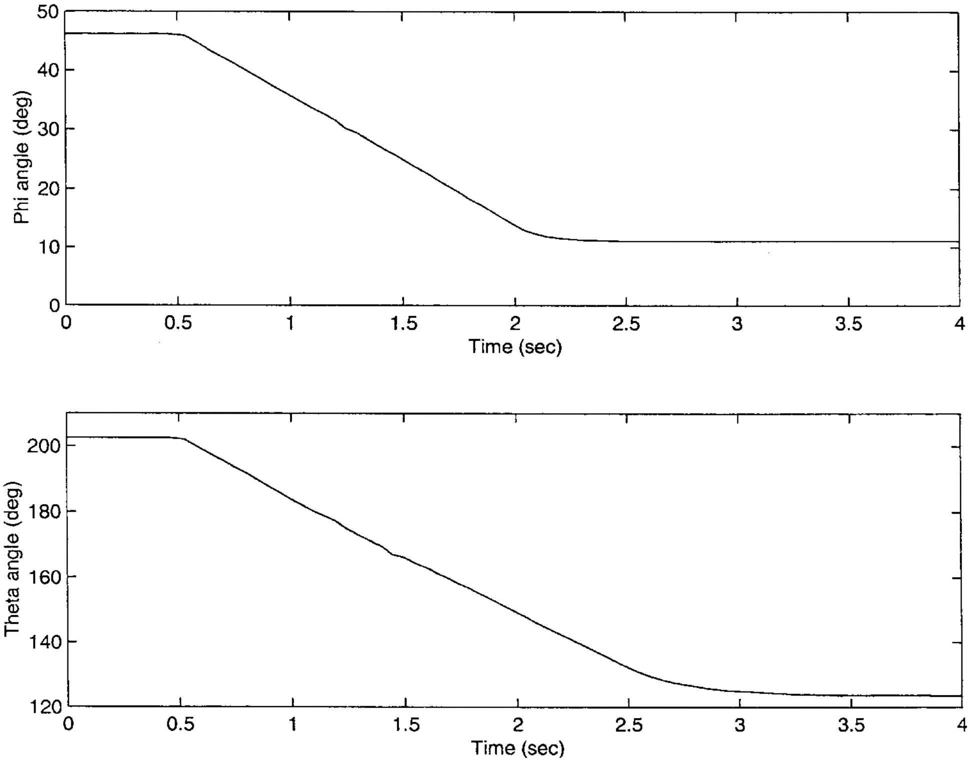

Fig. 15 Joint variable trajectories during move to localizer position command

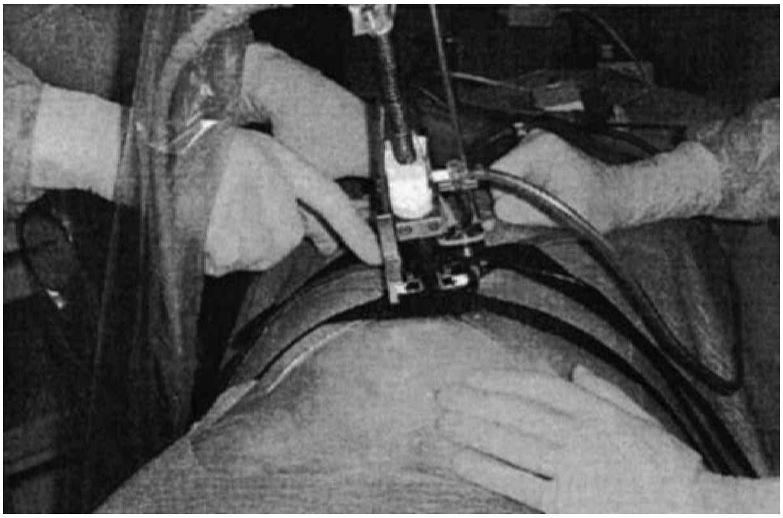

Fig. 16 Endoscope robot set-up on cadaver abdomen

is awkward and inadvisable owing to sterility considerations. The straps should be held by clamps at the sides of the table.

2. A wider open space is needed at the base of the device to enable the use of trocar attachments used at the incision point.
3. The cable that controls the insertion of the endoscope must be easily detachable so that the endoscope may be removed to clean the lens. This has been accomplished by providing a slot for quick manual cable detachment.
4. The range of angular motion for the endoscope in inclination must be increased to less than 10° from the horizontal in order to visualize the abdominal wall. The present prototype is limited to 30° from the horizontal. This capability above all is critical to the usability of the device.
5. The robot must be easily removable from the abdomen without removing the trocar from the incision.
6. The vertical passage of the actuator cables and sleeves is an annoyance and may block sight lines to the video monitor during surgical procedures.

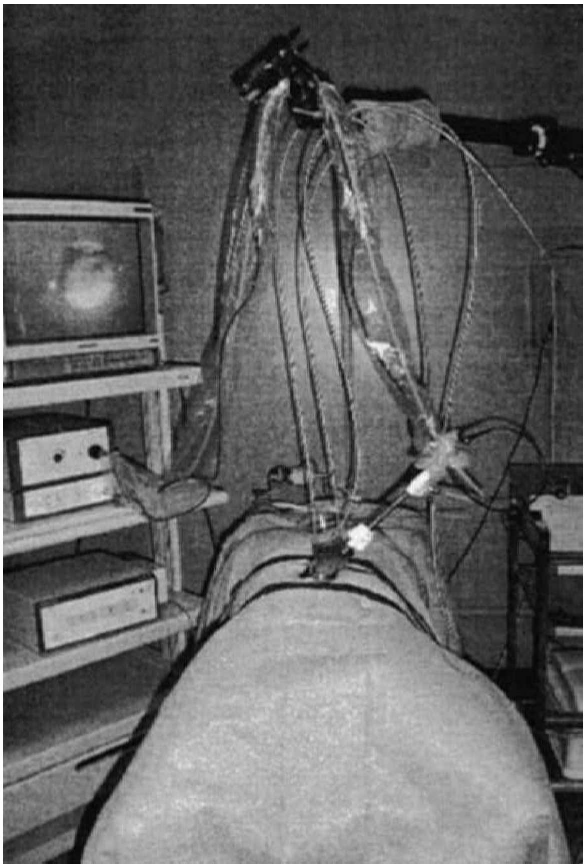

Fig. 17 Endoscope robot trial on cadaver abdomen

7. The height of the trocar clamp attachment should be reduced so that shorter trocars can be inserted further into the abdomen to obtain a more airtight seal at the incision.
8. The device should be adaptable to the dimensional variations of different makes of endoscopes and trocars rather than a single model.

In other comments, the low weight, small size and simplicity of the device were seen as significant advantages compared with conventional endoscope manipulators, and it was strongly suggested that adding weight and complexity to the device should be avoided.

5.2 Modified prototype

In response to the end-user comments given by the surgical experts, a modified prototype endoscope manipulator mechanism has been designed. The overall size, mass, configuration and function of the device remain largely unchanged, but the dimensions and shapes of the parts of the device have been modified in order to obtain a larger range of motion, in order better to accommodate different trocar configurations and in order to facilitate removal of the robot from the abdomen while leaving the trocar inserted in the endoscope incision. The modified design is shown in Fig. 18 and the fabricated modified prototype mechanism, not including the miniature motors, is pictured in Fig. 19.

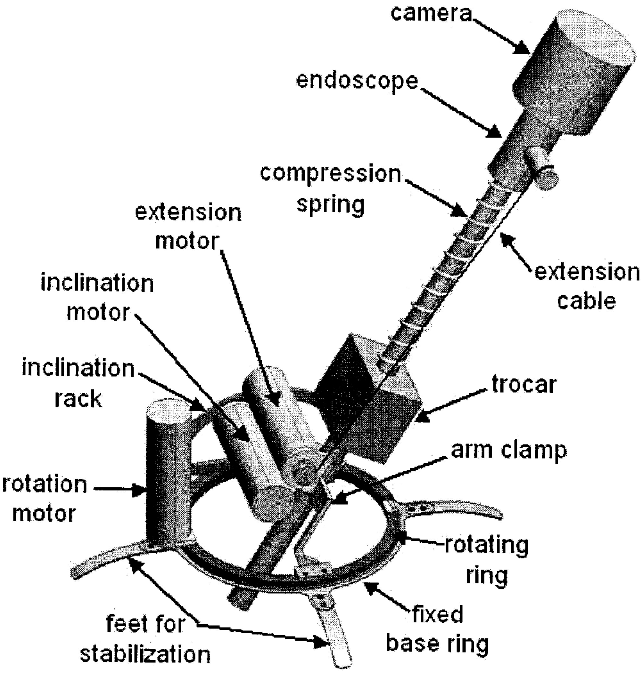

Fig. 18 Modified prototype schematic model

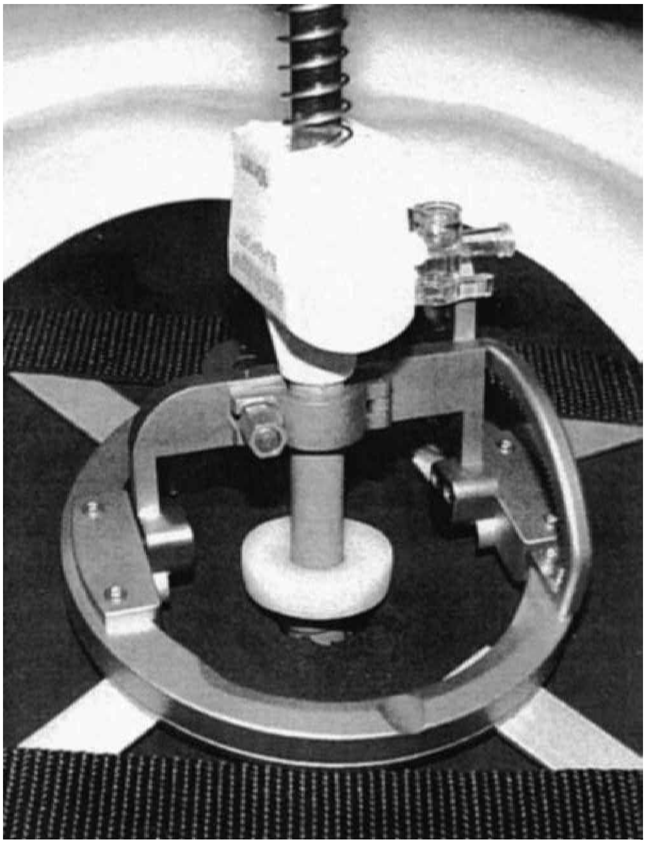

Fig. 19 Modified prototype

The larger 90 mm inner diameter and lower 2.5 mm height of the base ring enables the trocar to be inclined to within 10° of the horizontal plane, while the 102 mm outer diameter does not significantly increase the total area occupied by the device on the abdomen. The lower and wider dimensions of the trocar clamp arm allow shorter trocars to be inserted further into the abdomen and provide space for additional trocar attachments around the incision point.

In addition, the use of lightweight, compact, sterilizable gearmotor assemblies directly integrated in the endoscope robot mechanism is proposed in order to eliminate the need for the cables and flexible sleeves between the mechanism and the actuator enclosure. A supplier has been identified to provide brushless d.c. motors with the specialized fabrication techniques and materials to withstand repeated autoclave cycles. The three gearmotor assemblies have a mass of less than 100 g each. Since conventional motor encoders are not autoclave proof, linear outputs from the Hall effect shaft position sensors in the brushless motors will be used for the feedback necessary for precise position control. The gearmotors are specified to be backdriveable so that the endoscope may be positioned manually if desired.

6 CONCLUSION

The progress and results obtained from the current endoscope manipulator prototype and the testing of the device on a cadaver have been encouraging, and the objective is to refine the design and command interface to proceed towards clinical testing *in vivo*. The novel features of the described endoscope manipulator are that it is sufficiently small and light for the positioning mechanism to be fixed directly on the abdomen. A novel hands-free robot command interface has also been implemented for automatic movement of the endoscope to centre the camera view on the tip of a selected instrument by using an external optical localizer to track the motion of the instrument.

An early prototype performed adequately, but it was complicated to operate and encountered difficulties in robustness and reliability. These shortcomings were corrected with the current prototype by the use of a different positioning mechanism and actuators. Further modifications to the shape of the current prototype parts are proposed in order to obtain a greater range of motion, in order to simplify further the set-up and operation of the device and in order better to accommodate a wide variety of endoscopes and trocars. Small gearmotors can be integrated directly in the mechanism to eliminate the use of cable actuation.

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