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DESIGN OF A MODULAR, PARTIALLY DISPOSABLE ROBOT FOR MINIMALLY INVASIVE SURGERY

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BACKGROUND

Most robots for minimally invasive surgery (MIS) are large, bulky devices which mimic the paradigm of manual MIS by manipulating long, rigid instruments from outside the body [1]. Some of these incorporate "wristed" instruments to place some local dexterity at or near the tool tip [2]. In contrast, a small number of MIS robot designs place all of the degrees of freedom inside the patient's body in order to increase the local dexterity [3].

Currently, the applicable scope of robots for MIS is limited. The da Vinci Surgical System (DVSS) is only optimized and most often used for a specific range of procedures, mainly excisional. Furthermore, only a quarter of hospitals in the United States own a DVSS [4]. The drawbacks of this system and others are the lack of capability to reconfigure the device's structure to accommodate different procedures and workspaces and the cost to own and operate one of these devices. These factors restrict robotic MIS to a relatively small patient base. An inexpensive and adaptive design for MIS would move toward making the improved surgical outcomes of robotic surgery available to a wider population.

In this paper we present the design of a small, insertable MIS robot with considerations for modularity of link geometry and disposable components in order to reduce cost and increase flexibility for adapting to patient-specific needs. The robot is intended to perform functions typical of other robotic MIS devices, such as tissue manipulation and retraction, in common surgeries such as cholecystectomy and appendectomy.

METHODS

A robotic surgical device is developed in this work. Modularity is implemented into its structure, allowing its kinematics to be changed according to the needs of the specific procedure to be performed. Inexpensive mechanical elements are utilized and the device is structured to reduce cost and favor single-use. Although the final product of this concept would ideally be as capable as the DVSS in terms of size and strength specifications (between 5 and 8 mm outer diameter [5] and 5 N at the instrument tip [6]), the proof-of-concept prototype developed in this work is scaled up in size.

The main subsystems of the robot include an external motor package, a modular port, a cable driving mechanism, a cable routing system, and an instrument tip. The motors are all placed externally, allowing for reusability. Since they are external and are not limited by space constraints inside the body, more expensive, high-performance actuators are not required.

The cable driving mechanism (Fig. 1) is designed for simplicity and modularity. Gear racks on parallel linear tracks are driven by gears on the motor shafts to actuate the cables.

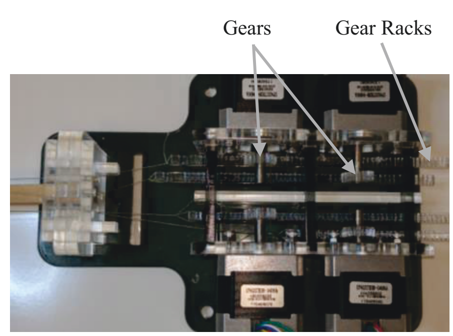

Figure 1. Gear racks for cable actuation.

The modular port (Fig. 2) allows the robotic articulation and instrument tip to be attached and driven by the motor package. Different cable-driven tools can be adapted to this port and quickly swapped in/out. Interfacing the kinematic control simply requires slipping cable end-loops over the hooked ends of the gear racks. This increases the tool's ability to be inexpensive and disposable. This also allows for different types of tool arms, configured with different kinematics, to be interchanged when needed.

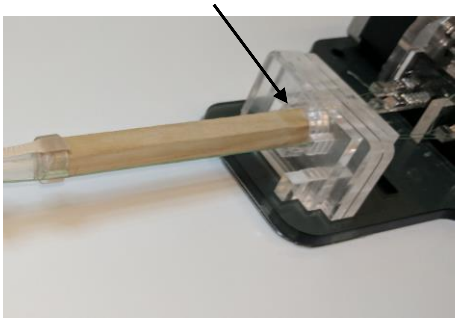

Figure 2. Modular port connecting instrument to motor base.

A routing manifold directs cables (Fig. 3) at each rotational joint of the robotic articulation such that cable tensions pass through or near the axis of rotation and do not produce coupled joint moments.

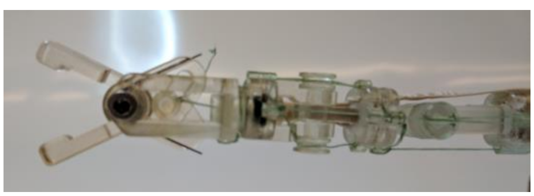

Figure 3. Tool arm with cable routing manifold.

A prototype robot was implemented with three degrees of freedom (pitch, yaw, and roll) and a simple grasper instrument tip. Each of these degrees of freedom are operated via one motor actuating one cable, permitting simple control and setup of the tool arm and reducing the number of cables by half compared to typical cable driven robots. The cable used in this prototype was common braided fishing line, which was strong and did not strain noticeably under tension. Each cable's actuation is counteracted by an elastic antagonist component, either elastic bands in the pitch and yaw or small torsion springs in the roll and grasp. These antagonists retain tension in the cables when the motors reverse to release tension on the cables. This eliminates the need for complex cable tensioners within the tool arm. The elastic bands were chosen as an inexpensive and disposable method of counteracting cable tension. In future iterations of the device, elastic bands will also be easier to reduce in size along with the rest of the device compared to torsion springs.

Most of the components were laser cut in acrylic or 3D-printed in acrylonitrile butadiene styrene (ABS). The overall outer diameter of the robotic instrument was 18 mm. Proof-of-concept testing was performed using a benchtop power supply, an Arduino microcontroller with a joystick pad for control, and grasping on various small objects.

RESULTS

The functionality of the prototype shows that the design elements implemented with the goals of modularity and inexpensive design can create a functional device. The gear-rack motor package effectively provides linear actuation to the cables, providing sufficient power to transmit motion in the various degrees of freedom on the tool arm of the device.

The modular tool arm port allows for simple and quick placement and removal of the tool arm to interface with the motor package. During testing, the tool arm of the device frequently needed to be attached and removed as adjustments and iterations were implemented. The application of the modular port made this easy, validating its practicality as a component.

The pitch, yaw, and roll degrees of freedom operated as intended. The pitch and yaw, which function mechanically the same, both rotate around their axes in a 180-degree arc. The elastic bands were shown to be effective when tensioned properly in the device's construction. A concern with the use of elastic bands on the device is that they will fatigue. Ideally, further investigation of durable elastic band materials would be merited. The device is intended to be used once before being disposed of, so higher quality elastic bands in later iterations will not be used to the point of fatigue failure. During repeated testing, failure occurred in the elastic bands when they were not tensioned properly, such that the maximum extension of the joint exceeded their yield strength. The bands did not fail when they were tensioned within a viable range. The adhesive that was used to apply the bands to the plastic of the joint also reduced the compliance of the bands, causing them to fail. This reason for failure was avoided by applying minimal amounts of the adhesive. Other methods of attaching the bands might also be explored to avoid this. The roll joint was able to rotate 270 degrees around its axis without damage to the small torsion spring. This degree of freedom did not fail during any tests.

In developmental iterations of the device's tool arm, tension in the cables operating the distal degrees of freedom restricted movement in the proximal degrees of freedom. The cable routing manifold was put in place to redirect tension forces in the tool arm to prevent distal interference. The manifold proved successful in that tension on the more distal degrees of freedom did not entirely restrict the motion of proximal degrees of freedom. The manifold, however, introduced friction into the distal cables' motion. The roll joint, the second most distal degree of freedom, had difficulty overcoming the friction to return to its start position after the cable tension had rotated it 180 degrees. As a result, it slowly moved back to its original position, which is not desirable. The most distal degree of freedom, the grasper, was not able to actuate due to the friction in its cable routing. The tension in the cable was able to hold the grasper's position, if it was pinched shut for instance, but the cable could not bring the grasper to that position.

Much of this friction can be attributed to the size of the device and the materials used. A slimmer, later iteration of the tool arm would reduce the cable path lengths through the manifolds, creating less friction on the cable. The cable used in the proof of concept also tended to hold its shape after being held in tension for a time, which contributed to the resistance in the device.

INTERPRETATION

The design elements implemented in this proof-of-concept device have shown to be effective, having an interchangeable tool arm system that would permit its use in a broader spectrum of surgical procedures than other devices currently on the market. The design approach emphasizing degrees of freedom operated by single cables, simple mechanical systems in the tool arm, and the external motor package will allow the device's tool arm to be inexpensive, disposable, and easily replaceable while the more expensive, electronic components remain external to the patient and reusable.

Many of the limitations of the device are due to the materials that its components are made of in the current iteration. The cables used in this iteration were strands of fishing line that were stiff such that they held their shape after being held in tension. Replacing these cables with a stronger, finer material that does not hold its shape when tension is relaxed (i.e., having lower flexural stiffness due to smaller cross-section) would mitigate some of the issues with friction and reduced maneuverability. Stronger plastics or inexpensive metals would allow the design of the device to reduce to a similar size as other tools which are already in use. A smaller profile, which would reduce friction in cable manifolds due to smaller path lengths, would increase its maneuverability. A smaller profile was not possible to develop in this proof of concept due to the materials that were used (ABS and laser-cut acrylic tended to break easily in smaller parts).

Future work, using this proof of concept as a foundation, would push further toward the goals of increased kinematic modularity and reduced cost. Adding modularity at each degree of freedom would allow for fully customizable kinematics of the tool arm, which could be reconfigured for any given procedure. A software interface may also be developed to facilitate planning the configuration of the device depending on the surgery type.

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