Proceedings of the 2020 Design of Medical Devices Conference
DMD2020
April 6, 7-9, 2020, Minneapolis, MN, USA

DMD2020-9015

A WIRE-DRIVEN MULTIFUNCTIONAL MANIPULATOR FOR SINGLE INCISION LAPAROSCOPIC SURGERY

A M Masum Bulbul Chowdhury
College of Aeronautics and Engineering
Kent State University
Kent, Ohio, USA

Michael J. Cullado
Summa Health System
Akron, Ohio, USA

Tao Shen*
College of Aeronautics and Engineering
Kent State University
Kent, Ohio, USA

ABSTRACT

Minimally Invasive Surgery (MIS) has gained popularity in current abdominal surgical procedures due to its reduced skin incision length, shortened recovery time and decreased postoperative complications. One trend is to enhance these benefits by developing technologies to expand the application of single incision laparoscopic surgery (SILS) which has even less incision and incision-related complication. However, the practical application of SILS has been constrained by many complexities, including fundamental procedure issues (e. g. limited space), as well as the issues related to surgical tools, such as lack of actuation force, weak tool tips, poor visualization and lack of dexterous multitasking tools. Due to this lack of multitasking tools, the surgical tools or robots have to be retracted, exchanged and reset multiple times during the surgery, increasing the surgical time, the risk of injury and the surgeon's level of fatigue. This paper focuses on developing a multifunctional manipulator with an automatic tool changing capability to boost practical application of SILS. The manipulator uses a wire-driven method that minimizes the potential damage from sterilization since the electronic actuation and sensing components are located remotely from the end-effector which needs heat or chemical sterilization before surgery. The feasibility of the tool tip changing method has been demonstrated by experiments.

Keywords: Minimally invasive surgery, Single incision laparoscopic surgery, multifunctional manipulator, wire-driven

INTRODUCTION

Minimally Invasive Surgery (MIS) is currently gaining popularity with its superiority to traditional open surgical procedures that are involved in making large incisions. Traditional open surgical methods are well familiar because of their ease of operation and relatively lower expenses, while these benefits are compromised by some fundamental disadvantages such as excessive bleeding, prolonged recuperation time, severe pain after surgery, high risk of infection, and unwanted scars [1]. These drawbacks eventually make traditional open surgery methods unappealing to the surgeons and patients. On the other hand, the MIS methods offer reduced pain after surgery, shortened recovery time and improved cosmetics while keeping the outcomes of equivalent open procedures [2-4]. Albeit MIS has its great benefits from patients' standpoint, it still poses some major challenges to surgeons as well as to the existing technology. The challenges include fundamental procedure issues (e. g. limited space), as well as some issues related to surgical tools, such as lack of actuation force [5], weak tool tips, poor visualization and lack of dexterity [6].

Single Incision Laparoscopic Surgery (SILS), the latest advance in MIS procedure, even enhances the benefits from traditional MIS procedures with its even less incision and incision-related complications [7]. However, tools for SILS meet the challenges not only from traditional MIS tools but also from the issue of lack of multitasking functionality. Without multitasking tools, if the surgeons need to change tools which is inevitable, they have to remove the tools and reset the system which increases the surgical time, the risk of injury and the surgeons' level of fatigue [8]. Instrument changing usually takes

* Corresponding author: tshen3@kent.edu

up as much as 30% of surgical time [9] which increases the rate of secondary injury and decreases patients' safety. This motivates the research for inventing assistant robots for tool handling and changing. Friedmand et al. [10] proposed a tool rack sub robotic system to hold surgical instruments and assist tool tip change for Da Vinci robot. This system shortens the time of tool tip change to some degree, while it still needs to retract the tools and reset the system in which the complexity and injury chance still exists. McKinley et al. [11] proposed an interchangeable surgical instrument system to simplify the tool change procedures. This procedure is aimed to realize tool changing in the body cavity, while it is only for MIS with multiple incisions instead of SILS. A previous research had designed a multifunctional manipulator which could realize automatic tooltip change in the body cavity by using two on-site tiny DC motors that works in an alternative cooperation [12]. This method eliminates the retraction step and is suitable for SILS application, while it also has a drawback as it has a high chance of damage from sterilization with the onsite DC motors and sensors.

Inspired by this fact, this paper explores the feasibility of a wire-driven actuation in a multifunctional manipulator that has the functionality to realize automatic tool changing for SILS. The concept design is to support automatic, fast and efficient tool changing desired by the surgeons. The detailed design of the manipulator is present in this paper. Experiments are conducted to demonstrate the functionality and effectiveness of this actuation method.

METHOD

The prototype of the multifunctional manipulator, as shown in Figure 1, is a cylinder shape with 24 mm in diameter and 46mm in length. The tool tip change and operation (e.g. open/close) functionality is realized by a wire-driven method There are no direct motors or sensors directly embedded in the mechanism. The wires will be driven by a precise electronic actuation remotely, eliminating the possibility of damage from sterilization.

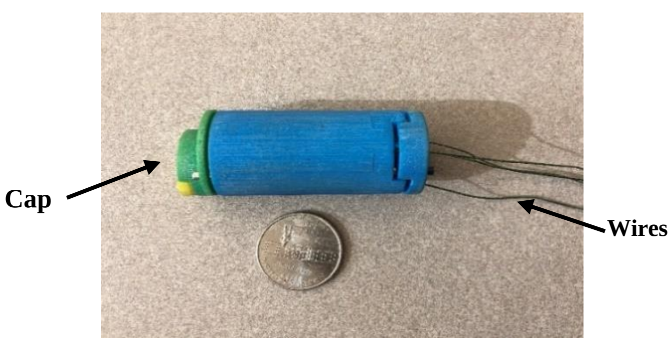


FIGURE 1: MULTIFUNCTIONAL MANIPULATOR PROTOTYPE

The multifunctional manipulator is composed of a tool tip container, an outside cover, a cap and relevant mechanical components (e. g. pulley, bearing), as shown in Figure 2 (a). The tooltip container can contain up to 3 tool tips, as shown in Figure 2 (b). The specific tool tips will be determined by laparoscopic surgical tasks. Here we just build three similar tool tip modes with different color. Two wires were wound at the bottom shaft of a tool tip container: the lower wire was wound clockwise, and the upper one was twined counterclockwise, as shown in Figure 3(a). By pulling the upper wire, the container can rotate counterclockwise; and by pulling the lower wire, the container can rotate clockwise. Through this rotation, a needed tool tip can be selected, then waiting to be deployed and operated. These two wires will be driven by remote power actuation. The function of deploying and operating the surgical tooltip is realized by pulling another pair of wires fixed on a nut which can move up and down along a lead tube, as shown in Figure 3(b). The slot at the bottom of the selected tool tip is docked with the extended part of the nut, thus moving the nut can realize the tool tip moving up and down. Once the upper part of the tool tip reaches the top hat, it will be locked with the hat by rotating tooltip container, thus the up-and-down movement of the nut can be used to operate the selected tool tip. At each place where the wires need be redirected, a tiny pulley (not shown in the pictures) is placed.

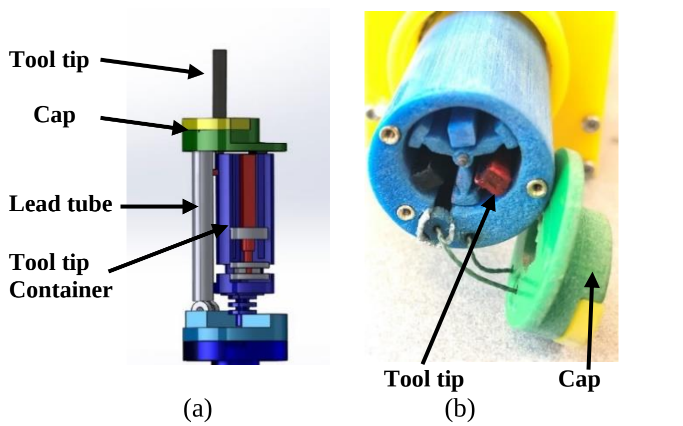


FIGURE 2: MULTIFUNCTIONAL MANIPULATOR COMPONENTS: (a) INSIDE STRCTURE; (b) TOP VIEW for INSIDE STRUCTURE

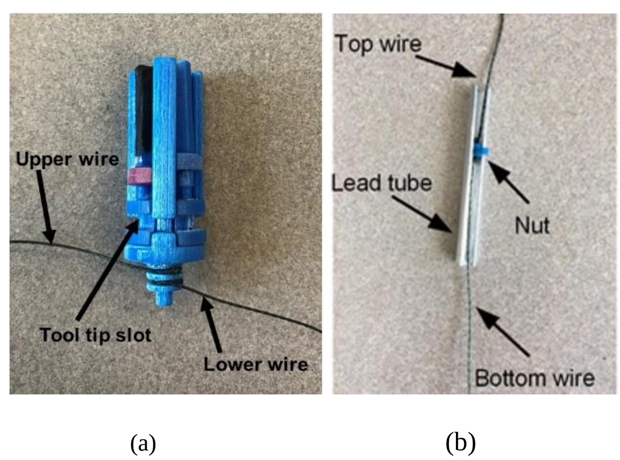
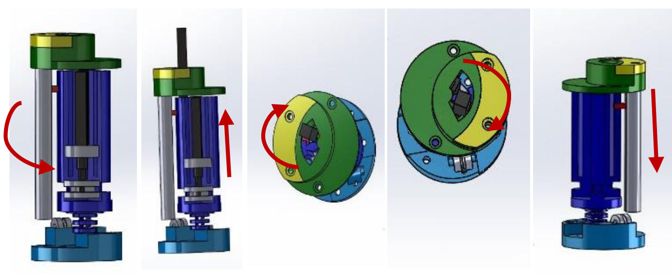


FIGURE 3: WIRE ACTUATION METHOD (a) CONTAINER ROTATION; (b) TOOL TIP ADVANCEMENT AND OPERATION.

To switch current tool tip to a new selected one, the tool tip container is rotated to unlock the upper part of the tool tip, and then the nut retracts the tool tip. A new tool tip is selected and deployed in the same way as the old one. Figure.4 shows all the sequences of a tool changing operation and retracting after surgery: (a) tool selection is made by rotating the tool tip container (b) tool advancement made by pulling top wire attached to the nut, (c) tool gets locked, (d) tool gets unlocked after using the tool tip, (e) tool retraction made by pulling bottom wire attached to the nut, and wait for next tool tip advancing. This sequence is motived by the previous work which has onsite DC motor actuation [12]. With this direct wire driving for rotational and translational movement instead of tiny motor driving rotation and lead screw advancement, the method proposed in this paper can expedite the tool tip changing and increase the tool tip operation force.



(a) (b) (c) (d) (e)

FIGURE 4: TOOL CHANGING SEQUENCES (a) TOOL SELSCTION (b) TOOL ADVANCEMENT (c) TOOL LOCKING (d) TOOL UNLOCKING (e) TOOL RETRACTION

RESULTS

The rotation of tool tip container makes equal change in length for the attached pair of wires, thus the length of the pair of wires can be controlled by a single remote actuation. This is the same as the change in length for the pair of wires in the translational nut movement. Therefore, two DC motors (Uxcell 12 V DC 200 RPM micro gear box Motor) are placed in a motor house to actuate the two pairs of wires, as shown in Figure 5. In each section for actuation, the wires were routed through several pulley for redirecting. As shown in Figure 5(b), the pair of wires for tool tip container rotation are twined on the actuation shaft with one clockwise and the other counterclockwise. The other section for the translational nut movement is designed with the same way. Arduino Mega is used to build the control system to actuate the motors to change the length of the wires.

The tool tip container holds three tool tips of three different colors- blue, red and black. Two tool tips have been manipulated (Blue and Black) in this experiment to demonstrate the feasibility of the proposed method. The entire operation is divided into 5 steps, following sequence in Figure 4, and we have observed the time taken for each step. The time taken for each of the steps are as follows: 1 second for tool selection, 3seconds for tool advancement, 0.5 seconds for tool locking, 0.5 seconds for tool unlocking and 3 seconds for tool retraction. The success of the tool tip change, as shown in Figure 8, demonstrates the feasibility of the proposed method. The entire process takes about 8 seconds to be completed. Tool advancement and retraction takes longer time as the nut advancing the tool tips need to travel a certain distance. Compared to the tool changing with onsite DC motor actuation in [13] which needs 21.8 seconds to realize a tool tip changing, the time taken by the proposed wire-driven actuation is only 8 seconds, showing a significant benefit in time reduction. This automatic procedure would significantly reduce the time required for surgeons to manually change tools and reduce possible risks associated with it.

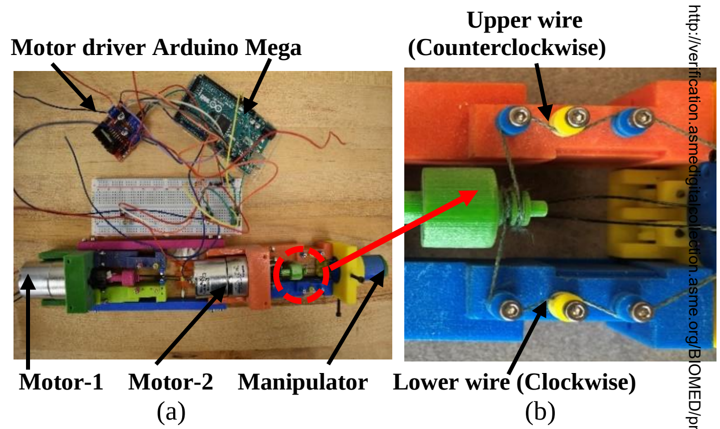
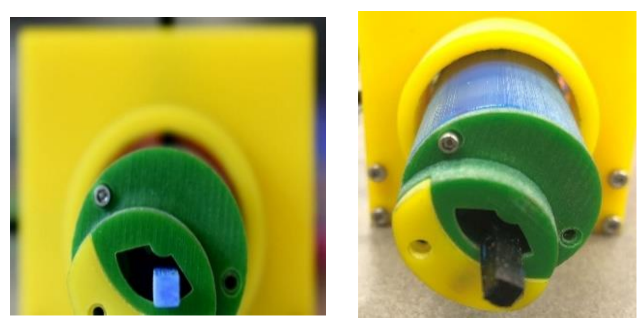


FIGURE 5: MOTOR HOUSING FOR EXPERIMENT



(a) (b)

FIGURE 6: TOOL TIP CHANING: (a) BLUE (b) BLACK

INTERPRETATION

This paper presents a multifunctional manipulator with a wire-driven method to improve the practice of SILS with an automated tool changing functionality. It simplifies the operation of tools/robots for laparoscopic surgery with significant reduction in tool changing operation time. Moreover, the wire-driven method minimizes the potential damage from sterilization since the electronic actuation and sensing are remotely located where no heat or chemical sterilization process is needed. The experiment shows the wire-driven method can actuate rotation and translation movement to change the tool tip from one to the other, which demonstrate the feasibility of the proposed approach. The time to complete a tool tip changing is only 8 seconds which is much less than that with ordinary manual tool changing method in [14], showing the effectiveness and efficiency of the proposed method.

Current prototype is still under research and has wire tensioning issues. Future work will focus on exploring a better wire tensioning method. Also, future work will integrate this manipulator with an articulated robotic arm and seek SILS clinical test.

REFERENCES

[1] Greaves, N., & Nicholson, J. 2011, "Single incision laparoscopic surgery in general surgery: a review," *The Annals of The Royal College of Surgeons of England*, 93(6), 437-440.

[2] Rohan, K., Xia, B., Yamakawa, Y., Ueda, J., Honda, H. 2017, "Design and Analysis of a Symmetric Articulated Single-Port Laparoscopic Surgical Device," *Design of Medical Devices Conference. American Society of Mechanical Engineers Digital Collection*, paper No: DMD2017-3441, V001T08A018; 2 pages.

[3] Zhao, Baoliang, and Carl A. Nelson. 2014, "A cable-driven grasper with decoupled motion and forces," *Journal of Medical Devices* 8.3, 2014: 030922.

[4] Vestweber, B., Alfes, A., Paul, C., Haaf, F., & Vestweber, K. H.,2010, "Single-incision laparoscopic surgery: a promising approach to sigmoidectomy for diverticular disease," *Surgical endoscopy*, 24(12), 3225-3228.

[5] Shen, T., Nelson, C.A., Bradley, J. J., 2019, *Journal of Intelligent& Robotic Systems*, 95: 473-489. https://doi.org/10.1007/s10846-018-0836-2

[6] Shen, T., Hennings, D., Nelson, C. A., & Oleynikov, D., 2018. "Performance of a Multifunctional Robot for Natural Orifice Transluminal Endoscopic Surgery," *Surgical innovation*, 25(4), 364-373.

[7] Chamberlain, R. S., & Sakpal, S. V., 2009, "A comprehensive review of single-incision laparoscopic surgery (SILS) and natural orifice transluminal endoscopic surgery (NOTES) techniques for cholecystectomy," *Journal of Gastrointestinal Surgery*, 13(9), 1733-1740.

[8] Mehta, N. Y., Haluck, R. S., Frecker, M. I., & Snyder, A. J., 2002, "Sequence and task analysis of instrument use in common laparoscopic procedures," *Surgical Endoscopy And Other Interventional Techniques*, 16(2), 280-285.

[9] Melzer A., "Endoscopic instruments: conventional and intelligent. Endosurgery," *New York: Churchill Livingstone*, 1996:69-95.

[10] Friedman, D.C., Dosher, J., Kowalewski, T., Rosen, J. and Hannaford, B., 2007, April, "Automated tool handling for the trauma pod surgical robot," *Proceedings of 2007 IEEE International Conference on Robotics and Automation* (pp. 1936-1941). IEEE.

[11] McKinley, S., Garg, A., Sen, S., Gealy, D.V., McKinley, J.P., Jen, Y., Guo, M., Boyd, D. and Goldberg, K., 2016, August, "An interchangeable surgical instrument system with application to supervised automation of multilateral tumor resection," In 2016 *IEEE International Conference on Automation Science and Engineering (CASE)*, pp. 821-826.

[12] Shen, T., Nelson, C., & Oleynikov, D., 2016, "Design and analysis of a bimanual multifunctional robot for NOTES," *Journal of Medical Devices*, 10(3), 030903.

[13] Shen, T., 2016, "Design, analysis, control and testing of a multifunctional NOTES robot," *Dissertation*.

[14] Kim, K. Y., Song, H., S., Suh, J. W., Lee, J.J., 2013, "A Novel Surgical Manipulator with Workspace-Conversion Ability for Telesurgery," *IEEE/ASME Transactions on Mechatronics*, 18 (1), pp. 200-211.