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Automatic Instrument Changer for Robotic Microsurgical Systems ⋆

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Abstract: This paper introduces a novel automatic instrument changer that allows for fast and precise tool changing in robot-assisted microsurgery. The importance of such a system is usually ignored and therefore most of the existing robotic surgical systems still require manual operation to change surgical instruments. To achieve automatic instrument changing, we apply a clamp mechanism which consists of an instrument adapter and an instrument holder. The instrument adapter creates a unified interface between the surgical instrument and the holder. The instrument holder clamps the instrument through the adapter. The instrument can be transferred to another holder when these two holders are connected. A prototype of the proposed automatic instrument changer was implemented and mounted on a surgical robot. The experimental results validate the capability of the prototypical design in automatic, precise, and fast instrument changing.

Keywords: Automatic tool changer, Microsurgical robots, Robot-assisted surgery.

1. INTRODUCTION

With the capability of precise and delicate manipulations, microsurgical robots have received significant attention in several clinical applications. For instance, prior research has resulted in the development of teleoperated systems [Yu et al. (1998); Gijbels et al. (2014); Wilson et al. (2018)] and semi-automated manipulators [Chen et al. (2018)] in robot-assisted ophthalmic surgery. To complete an operation in microsurgery, the use of multiple instruments with different functions is usually required. On average, a surgeon changes the instrument every two minutes in ophthalmic surgery [Nambi et al. (2016)]. However, most of existing robotic surgical systems are not capable of changing the surgical instrument automatically. Manual change of the surgical instrument leads to positioning inaccuracy and motion distortion [Nambi et al. (2015)]. A calibration process is thus necessitated, which is tedious, time-consuming, and not allowed during the clinical application [Üneri et al. (2010)]. Therefore, an automatic instrument changer is an essential technology to improve the time-efficiency and precision of robot-assisted surgery.

There are a few robotic surgical systems which have addressed the requirement of changing surgical instruments in the surgery. The Steady-Hand Eye Robot [Üneri et al. (2010)] redesigned the surgical instruments such that the interface between the surgical robot and every each instruments are identical. This unified interface eliminates the time-consuming calibration process and meanwhile ensures the positioning accuracy after the surgical instrument is changed [Fleming et al. (2008)]. However, manual changing and fixation of the instruments are still required in their system design. Besides, the redesign of surgical instruments is very costly in clinical applications.

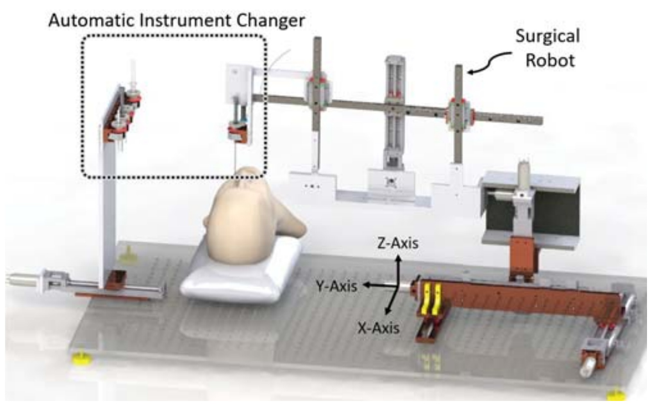

Fig. 1. The automatic instrument changing system mounted on the surgical robot.

Similar to the Steady-Hand Eye Robot, a Quick-Change Adapter is proposed to facilitate fast instrument changing [Nambi et al. (2015, 2016)]. Disposable microforceps and other required surgical instruments are combined with the Quick-Change Adapter, which is designed with self-alignment and fixation. The average time required to change an instrument was reported to be 12 s. However, this specific mechanism is only allowed for the manual

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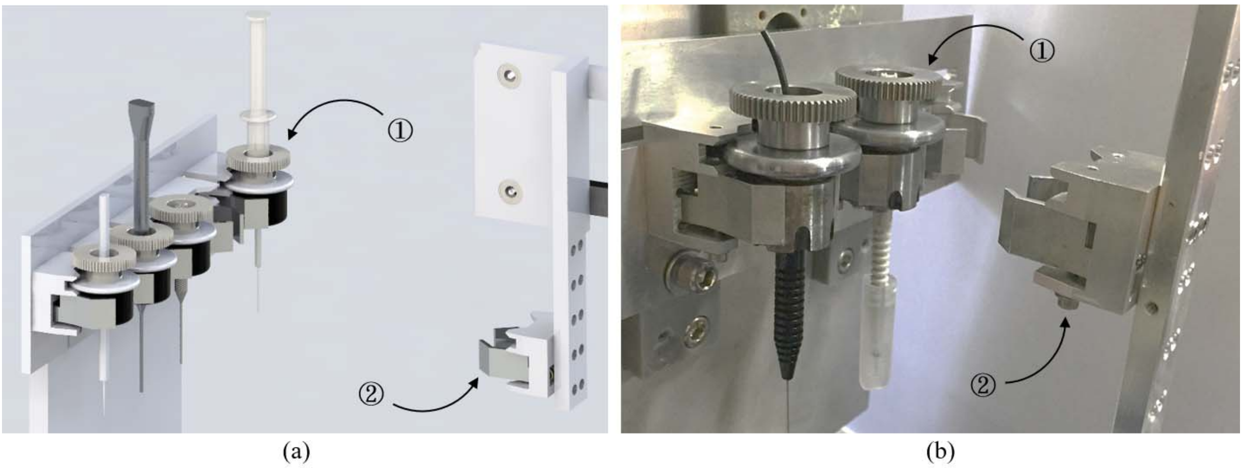

Fig. 2. The automatic instrument changing system consists of ① an instrument adapter and ② an instrument holder. (a) CAD model of the system. (b) Implemented prototype.

change of the instruments. Automatic instrument change is still not available.

To achieve automatic instrument change, a tool rack system is exclusively developed for the Da Vinci Surgical Systems [Friedman et al. (2007)]. The tool rack system can accommodate, accept, and dispense up to 14 surgical instruments. The tool is reliably installed in a sterilizable turntable in a standard-compliant manner to accommodate misalignment during a tool change. The resulting design has been integrated and tested with the Trauma Pod system and meets all of its design requirements. However, the overall system is bulky and not suitable for robot-assisted microsurgery. In their design, a subsystem is required to transport the surgical instrument between the robot and the tool rack, which results a limited speed of instrument changing and increases the complexity of the system design.

In this paper, a novel automatic instrument changer is proposed for a microsurgical robot as illustrated in Fig. 1. Referring to the design of the automatic tool changer in CNC machines [Rogelio and Baldovino (2014); Lundberg (2011)] and multi-axis plotters, our design consists of two parts: an instrument adapter and an instrument holder. The instrument adapter provides an identical interface between the surgical robot and each instrument. This interface is created by a pair of off-the-shelf collet and nut, as the approach commonly applied to CNC machine tools. The instrument holder clamps the instrument through the adapter by spring force. The mechanism design of the holder allows the instrument to transfer to another empty holder when these two holders are connected. A coupler is designed to avoid misalignment between the instrument adapter and holder, therefore there is no need for calibration after the instrument is changed.

The main contribution of this work is proposing a mechanism design of a robotic instrument changer which enables automatic, precise, and fast instrument changing. The remainder of the paper is organized as follows: the system requirements and mechanism design are given in Section 2; the operational procedures are described in Section 3; Section 4 demonstrates the prototype of the proposed automatic instrument changer; the concluding remarks are given in Section 5.

2. SYSTEM REQUIREMENTS AND MECHANISM DESIGN

To improve the time-efficiency and precision of robot-assisted microsurgery, an automatic instrument changer is proposed and integrated with the surgical robot we have developed. In this section, the system requirements and mechanism design of the proposed automatic instrument changer are provided.

2.1 System Requirements

In order to accommodate common surgical instruments applied in vitreoretinal surgery, the automatic instrument changer has to allow for any instrument of the diameter ranged from 6.03 mm (e.g., DDS) to 9.33 mm (e.g., light probe). To avoid the calibration procedure after the instrument is changed, the adapter has to be fixed the instrument at a known vertical position from the tool-tip. To hold the instrument during the surgery, the holder must provide a static friction force more than 0.53 N, as analyzed in Section 2.3.

The detailed specifications of the automatic instrument changer are listed as the following:

(1) Accommodating the instruments of the diameter up to 10 mm.
(2) Fixing the instruments at the height of 70 mm from the tool-tip.
(3) Providing a static friction force more than 0.53 N.
(4) Allowing automatic instrument changing within 10 seconds or less.
(5) Able to rotate the instrument along its centerline.
(6) The procedure of instrument change shall not interfere with the surgical site, which is a $200 \times 200 \times 100 mm^3$ cube beneath the microsurgical incision.

Different from industrial CNC machines which usually performs high-speed rotation about the cutting tool, the rotational speed of surgical instruments are usually less

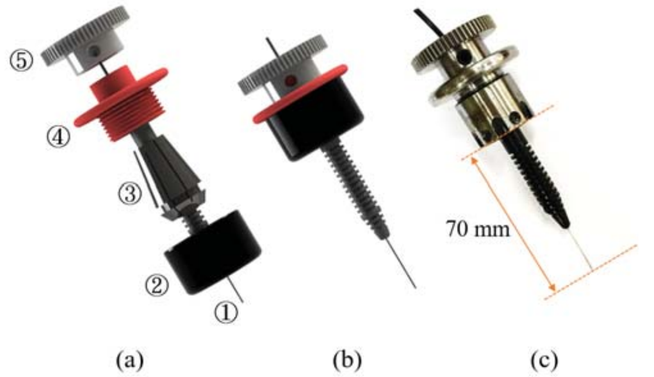

Fig. 3. The design and assembly of the instrument adapter. (a) Parts breakdown: ① surgical instrument; ② nut; ③ collet; ④ coupler; and ⑤ gear. (b) The integrated CAD model. (c) The fabricated prototype.

than 240 rpm. As a result, the surgical tool changer can be clamped by its side, while CNC cutting tools usually require top clamping.

2.2 Mechanism Design

The mechanism design of the automatic instrument changing system is shown in Fig. 2. We want to develop a rapid and reliable method for mounting and changing the surgical instruments. These instruments are assembled with the instrument adapter using collets and nuts. The disc-shaped protrusion on the instrument adapter can be coupled with the groove on the instrument holder. This design ensures there is no misalignment between the instrument adapter and holder, and therefore the requirement of re-calibration after each replacement of the surgical instrument can be eliminated. When the surgical robot wants to change the instrument, the instrument holder moves forward to another empty holder on the tool shelf by moving the 3-axis stage that carries the surgical robot. Once two holders are connected, the empty holder automatically clamps the surgical instrument. The instrument changing procedure is then completed when the two holders are disconnected again by moving the 3-axis stage. In this section, the detailed mechanisms of the instrument adapter and the instrument holder are introduced.

Instrument Adapter The mechanism of the instrument adapter is shown in Fig. 3. This project designs an instrument adapter that can stably place all surgical instruments. We apply an ER-16 collet to fix the surgical instrument, which accepts the instrument of diameter ranging from 1.0 mm to 10.0 mm. The paired nut is screwed at 70 mm above the tool-tip. In order to align the instrument adapter and holder, a disc-shaped coupler with an 8-degree bevel inner wall is designed to connect with the collet. In addition, the instrument rotation can be driven by a servo motor through an attached gear on the adapter. The maximum diameter of the instrument adapter is 30 mm.

Instrument Holder The mechanism of the instrument holder is shown in Fig. 4. This design is based on an antique 2-axis plotter (Roland DXY-1200) that allows rapid change of customized pens during printing. Above

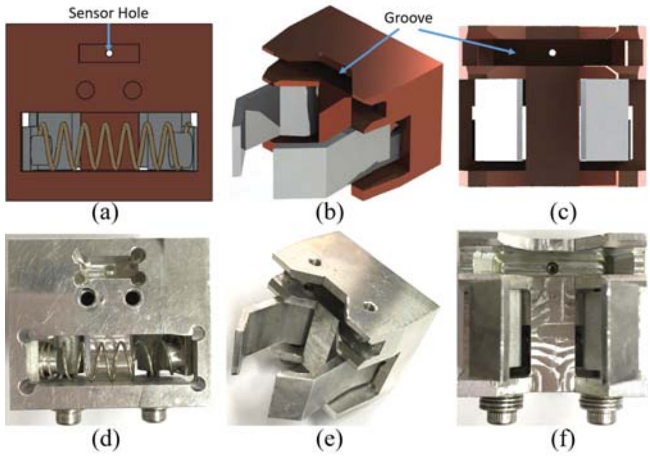

Fig. 4. The mechanism design of the instrument holder. (a)(d) Back view. (b)(e) Perspective view. (c)(f) Front view.

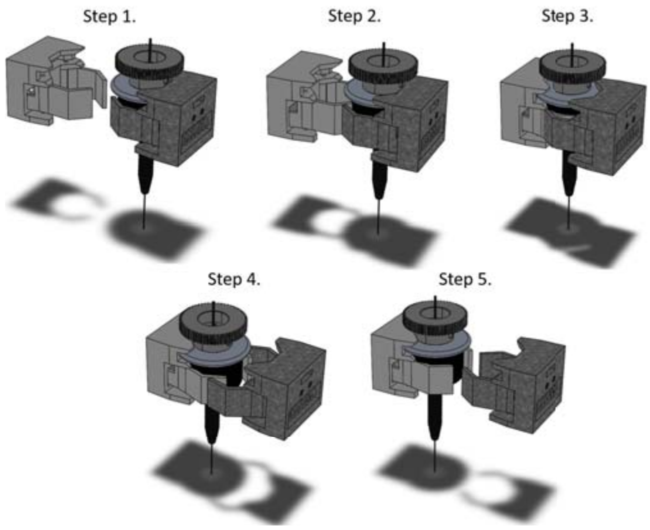

Fig. 5. The steps of transferring a tool to an empty holder.

the clips, there is a groove that matches the size of the coupler on the instrument adapter. In the groove, we install a switch sensor (Panasonic Detector Switches ESE11), which detects whether the holder holds an instrument. As shown in Fig. 5, when the instrument holder takes the instrument adapter, the width between two clips will be 2.74 mm greater than the one of an empty instrument holder. When two holders are connected, the clips on the empty holder will insert in between the nut and the clips on the holder holding an instrument. Once two holders are disconnected, the instrument is naturally transferred to the empty holder. By repeating this procedure, we can see the instrument is continuously changed from one holder to the other. The instrument adapter is clamped on the holder by a spring force around 0.81 N. To fit the size of the instrument holder, the spring constant is chosen to be 0.3 N/mm. The dimension of the spring is with 7 mm spring wire diameter, 30 mm free length of spring, and 8 number of active windings.

2.3 Spring Selection

In the design of the instrument holder, the choice of the spring constant is important. First, the spring must generate sufficiently large torque to clamp the instrument and make sure that the instrument does not fall when the robot is in use. Second, when two instrument holders are connected to exchange the tool, the external torque applied to the clamp should be greater than the torque generated from the spring force. Combining the above conditions, we obtain the upper and lower bounds of the spring constant.

The spring force applies a positive torque to the clamp through the lever principle. The force arm from the clamp to the fulcrum and the force arm from the spring to the fulcrum are 19.9 and 9.9 mm, respectively. When the tool holder faces the ground, the clamp must support the weight of the entire tool and adapter approximately around 1.06 N. The maximum displacement of the spring when the clamps are squeezed by the tool adapter is 7.68 mm. The angle between the gravity and normal force vector applied to the clamp is 51.4 degrees. Thus,

$$\begin{aligned} \tau_{spring} &\geq \tau_{gravity} \\ \Rightarrow 7.68K \cdot 9.9 &\geq 1.06 \cdot cos(51.4^{\circ}) \cdot 19.9 \\ \Rightarrow K &\geq 0.17 \end{aligned} \tag{1}$$

where K is the spring constant with the unit of N/mm. In the case of exchanging instruments between two holders, the torque generated from the motion of the motor-driven stage must be greater than the torque generated from the spring when the two holders are connected. The maximum compression of the spring when two sets of clamps are connected is 9.69 mm. The maximum force the ball-screw linear stage generates is 81.4 N. Hence,

$$\begin{aligned} \tau_{spring} &\leq \tau_{stage} \\ \Rightarrow 9.69K \cdot 9.9 &\leq 81.4 \cdot cos(51.4^{\circ}) \cdot 19.9 \\ \Rightarrow K &\leq 10.54 \end{aligned} \tag{2}$$

The acceptable range of the spring constant K is obtained by combining both the upper (Eq. 2) and lower bounds (Eq. 1). In our prototype, we select a spring with the spring constant of 0.33 N/mm.

3. OPERATIONS FOR INSTRUMENT CHANGING

In Section 3, we will introduce the setup of the automatic instrument changer on the microsurgical robotic system. As shown in Fig. 1, the surgical robot is carried by a 3-axis stage. This stage allows translational motions of the robot, which is critical in the alignment procedure to the surgical incision and in the operation of instrument change. The hardware architecture and trajectory planning for tool change are described in this section.

3.1 Hardware and Control Architecture

To allow for changing between multiple instruments, a tool shelf capable of mounting four instrument holders in a row is designed. Note this tool shelf can be easily expanded if more instruments are required. Besides, an instrument holder is attached to the surgical robot such that the robot can pick and return the surgical instrument during microsurgery. To avoid hitting the patient during the instrument changing operation, the working area and the exchange area are separated. The surgical robot is carried by the 3-axis stage that enables translational motion on X, Y, and Z direction, and the tool shelf is carried by a single-axis stage moving along the Y-axis direction. To avoid ambiguity, the motion of the tool shelf is labelled as Y'-axis. These two stages will move simultaneously when connecting two instrument holders for tool change.

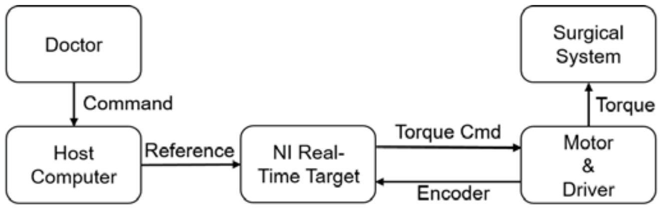

Fig. 6. The hardware architecture of the robotic surgical system.

The translational stages are constructed by single-axis ball-screw linear sliders (Hiwin KK4001/KK5002) with travelling range of 175/230 mm driven by DC servo motors (Faulhaber Micromotors Series 2642W024CR). The positions of the stage are measured from optical encoders. The specifications of the stages are summarized in Table 1. With this multi-axis stage, the robotic system has the freedom of movements in three directions so that it can select and exchange the required surgical instruments automatically.

Table 1. Specifications of the multi-axis stage which carries the microsurgical robot.

Motor	Count/Rev	Screw	Resolution	Speed
Z-Axis	1024	1 mm/cycle	244 nm/count	21.32 mm/sec
X-Axis	1024	2 mm/cycle	488 nm/count	42.62 mm/sec
Y-Axis	1024	2 mm/cycle	488 nm/count	42.62 mm/sec
Y'-Axis	1024	1 mm/cycle	244 nm/count	30.53 mm/sec

The hardware and control architecture of the automatic instrument changer system is shown in Fig. 6. The DC servo motors are driven by current type drive electronics. The surgeon is able to set commands on the host computer. The host computer then generates an instrument change trajectory to the NI Real-Time target which performs servo-level feedback control. To track the designated reference trajectory, the control of the DC servo motors is done by applying a typical PID control method with the control sampling rate of 1 kHz.

3.2 Planning of Tool Change Trajectory

The automatic instrument changer system needs to demonstrate the capability of grasping and returning an arbitrary surgical instrument during the microsurgery. The instrument changing operation is done by moving the stages carrying the surgical robot and the tool shelf. When the surgical robot is operating with the patient, the robot itself is aligned with the patient's surgical incision. On the other hand, the tool shelf will stay outside the workspace of the robot. Once the command of instrument change is placed, the tool shelf would go back to the position which is reachable by the surgical robot.

We assume that the positions of each instrument holder are known in advance. To change a surgical instrument, the robot moves to the position of 30 mm away from the tool shelf. Next, it aligns to the assigned empty holder and returns the instrument currently holding on the robot. After returning the instrument, the holder aligns to the desired instrument holder. Then, the holder picks up the new instrument and goes back to the initial position. As shown in Fig. 7, a standard operational procedure of tool change is summarized as the following:

(1) Initialize the stage position.
(2) Define the positions of every each instrument holders on the tool shelf.
(3) Drive the tool shelf to the surgical robot's workspace.
(4) Drive the surgical robot to the tool shelf and align the surgical robot to the empty instrument holder (T_1).
(5) Return the instrument (T_2).
(6) Align the surgical robot to the desired instrument holder (T_3).
(7) Grasp the desired instrument (T_4).
(8) Go back to the initial position (T_5).

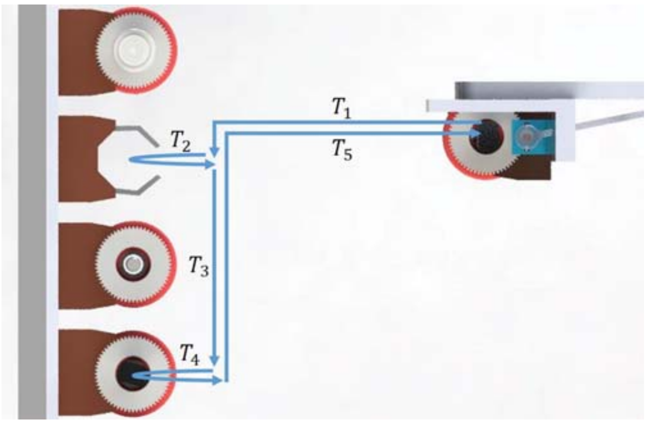

Fig. 7. Trajectory of the surgical robot for switching the instrument. T_1: The surgical robot is aligned to the empty instrument holder. T_2: The instrument is returned. T_3: The surgical robot is aligned to the desired instrument holder. T_4: The desired instrument is picked. T_5: The surgical robot moves back to the operational position.

4. EXPERIMENTAL RESULTS

The proposed design of the automatic instrument changer is implemented as shown in Fig. 2. Speed and repeatability experiments were conducted to evaluate the conceptual design and the implemented prototype.

4.1 Speed of Instrument Changing

In this experiment, the maximum speed to pick and return an instrument was evaluated. The instrument holder on the surgical robot was commanded to connect and disconnect with the instrument holder on the tool shelf by assigning a sinusoidal reference to the Y-axis stage. The

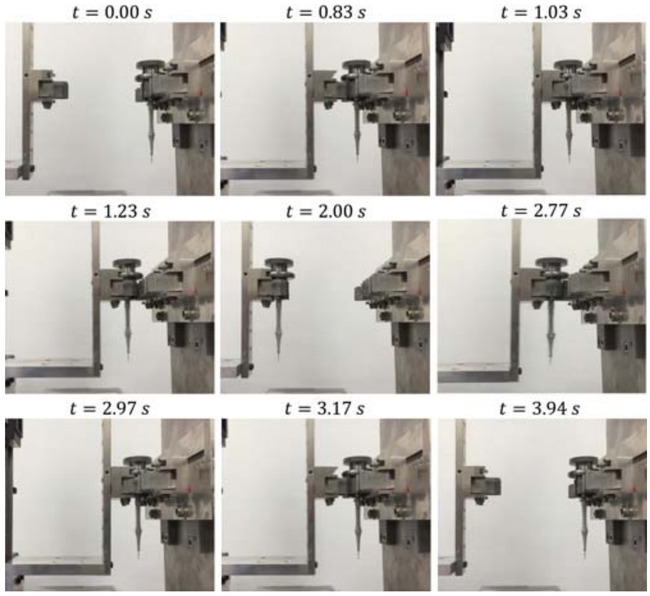

Fig. 8. Screenshots of the speed test. The surgical instrument is picked and returned within 4 s.

frequency of the sinusoidal reference was changed from 0.3 Hz, 0.5 Hz, to 1 Hz. The amplitude of the sinusoidal reference was chosen as 50 mm. For each frequency, 100 periods of the sinusoidal reference was performed.

The screenshots of the experiment with 0.5 Hz sinusoidal reference is shown in Fig.8. Since the two holders were connected every two seconds, it requires totally 4 s to pick and return an instrument. After completing 100 periods for each frequency, the success rates in 0.3 Hz and 0.5 Hz were both 100%. Unfortunately, the experiment with 1 Hz sinusoidal reference failed. This is because the 3-axis stage had reached its maximum motion velocity. We can conclude that the required time for grasping or returning an instrument is at least less than 2 s.

4.2 Repeatability of Instrument Changing

In this experiment, the precision of the automatic instrument changer was evaluated. We installed three ballpoint pens on the tool shelf with the color of red, blue, and black, respectively. In the experiment, the instrument holder picked a pen and drawn a circle with the diameter of 40 mm. Once finished, the pen was returned to the tool shelf. The same procedure were repeatedly performed until all the three pens had been used 7 times. To evaluate the performance, the roundness of each circle were selected as the performance index by [Cox (1927)]:

$$Roundness := \frac{4\pi \cdot area}{perimeter^2} \tag{3}$$

When a perfect circle was drawn, the roundness is of 1. Any distortion leads to a decreased roundness index.

The result for the drawn circles is shown in Fig. 9. Ideally, three circles would align together. However, the experimental result indicates the maximum error was around 0.51 mm. This error might be caused by the assembly error when installing the ballpoint pens on the instrument adapter. The roundness for every circle is listed in Table 2. The following observation are made. First,

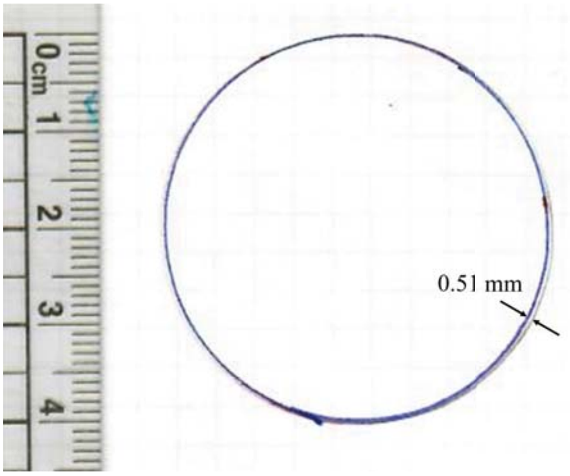

Fig. 9. The repeatability test demonstrated by drawing an identical circle using three different colors (in the order of blue, red, and black). The maximum error is 0.51 mm.

Table 2. The roundness of each drawn circle in the repeatability test.

Color\Test	1	2	3	4	5	6	7
Red	0.94	0.90	0.93	0.94	0.93	0.91	0.94
Blue	0.97	0.96	0.95	0.97	0.95	0.96	0.95
Black	0.93	0.95	0.96	0.94	0.94	0.93	0.96

all the circles have the roundness larger than 0.85. This verifies the control performance of the translational stages. Second, the roundness calculated from the circles drawn by the same ballpoint pen has a small variation. This validates the precision of the instrument adapter and the instrument holder. Third, the blue pen and red pen creates the largest and lowest average roundness, 0.96 and 0.93, respectively. This difference indicates the scale of the assembly error, which can be further calibrated by adjusting the position of the multi-axis stage.

5. CONCLUSION AND FUTURE WORK

This paper presents a novel design of the tool changer that enables automatic, fast, and precise instrument change in robot-assisted microsurgery. The developed changer is composed of an instrument adapter and an instrument holder. The adapter allows microsurgical instruments with the diameters up to 10 mm. Through our design, the adapter can be precisely retained in the instrument holder and be transferred when two holders are connected. An experimental prototype has been fabricated and assembled to evaluate the performance of the developed automatic instrument changer. The required time to pick or return the instrument was shown to be less than 2 s. The tool-tip precision after changing is demonstrated by drawing a circle of diameter 40 mm using ballpoint pens with different colors. The results indicate that the precision error of this prototype is around 0.51 mm. In the future, we will integrate the proposed tool changer with a surgical robot and calibrate the kinematic error to obtain better tool-tip positioning accuracy. The sterilization in clinical evaluation will also be considered in our future prototype.

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