A temperature-dependent, variable-stiffness endoscopic robotic manipulator with active heating and cooling

Le, Huu Minh; Phan, Phuoc Thien; Cao, Lin; Liu, Jiajun; Phee, Soo Jay

2020

Le, H. M., Phan, P. T., Cao, L., Liu, J., & Phee, S. J. (2020). A temperature-dependent, variable-stiffness endoscopic robotic manipulator with active heating and cooling. *Annals of Biomedical Engineering*, in press. doi:10.1007/s10439-020-02495-z

<https://hdl.handle.net/10356/137932>

<https://doi.org/10.1007/s10439-020-02495-z>

© 2020 Biomedical Engineering Society. All rights reserved. This paper was published in *Annals of Biomedical Engineering* and is made available with permission of Biomedical Engineering Society.

Downloaded on 26 Apr 2023 15:14:42 SGT

A Temperature-dependent, Variable-stiffness Endoscopic Robotic Manipulator with Active Heating and Cooling

Huu Minh Le, Phuoc Thien Phan, Cao Lin*, Liu Jiajun, and Soo Jay Phee

Robotics Research Center, School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore;

*Correspondence: Cao Lin. E-mail address: lin.cao@ntu.edu.sg

Abstract

In flexible endoscopy, the endoscope needs to be sufficiently flexible to go through the tortuous paths inside the human body and meanwhile be stiff enough to withstand external payloads without unwanted tip bending during operation. Thus, an endoscope whose stiffness can be adjusted on command is needed. This paper presents a novel variable-stiffness manipulator. The manipulator ($\varnothing 15$ mm) has embedded thermoplastic tubes whose stiffness is tunable through temperature. Temperature is adjusted through joule heat generated by the electrical current supplied to the stainless steel coils and an active air-cooling mechanism. Tests and modeling were conducted to characterize the performance of the design. The manipulator has a high stiffness-changing ratio (22) between rigid and flexible states while that of its commercial Olympus counterpart is only 1.59. The active cooling time is 11.9s while that of passive ambient cooling is 100.3s. The thermal insulation layer (Aerogel) keeps the temperature of the outer surface within the safe range (below 41°C). The models can describe the heating and cooling processes with root mean square errors ranging from 0.6 °C to 1.3 °C. The results confirm the feasibility of a variable-stiffness endoscopic manipulator with high stiffness-changing ratio, fast mode-switching, and safe thermal insulation.

Key terms: Minimally Invasive Surgery (MIS), NOTES, surgical robots, variable-stiffness endoscopes, variable-stiffness materials.

1. Introduction

Advanced surgical procedures like Minimally Invasive Surgery (MIS) or Natural Orifice Transluminal Endoscopic Surgery (NOTES) have numerous advantages over the conventional surgical procedures (open surgery) such as shortened hospital time, minimized post-surgery effects, better cosmetics, reduced patient's discomforts ^{2, 13}. In NOTES, the endoscope has to

be flexible to travel through sinuous paths to reach the target therapeutic site inside the human body without damaging tissues; once at the target site, the endoscope needs to be stiff enough to withstand external payloads as a stable platform during tissue manipulation without unwanted bending of the endoscope tip. This requirement is more critical in NOTES than other intraluminal endoscopic procedures because the endoscope may need to lift or manipulate large and heavy abdominal organs, as identified by the American Society for Gastrointestinal Endoscopy/Society of American Gastrointestinal and Endoscopic Surgeons²⁵. Thus, an endoscope whose stiffness can be adjusted on command is needed⁸. For variable-stiffness endoscopes for NOTES procedures, the main concern is still on the stiffness in rigid state. Existing flexible endoscopes, including those with variable-stiffness features, are still too “floppy” for NOTES procedures, as discussed in reference²⁷. Thus, endoscopes with higher stiffness in rigid state are needed to serve as stable platform for surgical instruments. To address this need, this study aims to design a variable-stiffness manipulator whose stiffness can be adjusted as needed in different surgical scenarios.

In the literature, a few variable-stiffness endoscopes have been developed. A simple mechanism is by tensioning or loosening the central cable so that the surrounding coil is compressed or decompressed resulting in different stiffness. With this technique, the variable-stiffness colonoscope from Olympus (model CF-240A) can achieve a limited stiffness ratio, 1.59, between the rigid state and flexible state of the bending section^{3, 28}. The stiffness of a manipulator can also be changed by reorganizing and/or reconnecting parts via attachable/detachable links²⁰. The flexible mode is obtained when parts are detached, and stiff mode occurs when parts are reattached. For instance, Yagi et al.²⁹ developed a rigid-flexible outer sheath for laparoscopic surgery using a multi-joint model and slider-linkage mechanism. In this design, if the inner channel is pressurized, the stopper will be engaged with the slider, resulting in the rigid mode; otherwise, the structure will stay in the flexible mode. An inflated tube has also been employed to stiffen a FORGUIDE shaft in²¹. High stiffness is achieved through the friction between a ring of cables which are located between the tube and the spring. In several other studies, the friction between rigid links could be controlled by cable tensions^{11, 14}. Recently, particle jamming technology based on granular materials, such as dry sand or coffee beans, is applied to tune the stiffness^{9, 10}. Grains are able to transform between compressed and loosen states by applying vacuum pressure. The main advantage of structure-based techniques is the ability to switch between flexible and stiff mode fast. However, the limitations include the limited stiffness-changing ratio, complexity in design with multiple parts involved (slider-linkage mechanism), the need of durable cables and links with complex control system or the coupling effect of the cable tensioning and position of the robot (cable tension based method), and requirement for substantial volume and high pressure (particle jamming technology).

Phase-changing materials can also be used for variable-stiffness manipulators, e.g., electrorheological and magnetorheological fluids^{23, 30}, phase changing alloy^{1, 5, 18}, and thermoplastic polymers^{6, 17}, which can change between various states under certain stimuli to regulate the stiffness. Researchers have built variable-stiffness catheters using electrorheological and magnetorheological fluids which change their states between liquid and quasi-solid states in electric and magnetic fields^{23, 30}. A mixture of indium, gallium, and

stannum has also been employed for a stiffness-adjustable platform for laparo-endoscopic single-site surgery¹⁸. Hot water at 89 °C was used to change the mode from rigid to flexible within 22 s; with 18 °C cold water, the reverse phase change was achieved within 15s. Recently, a low melting point alloy (Cerrolow 117), which can transform from solid to liquid phase upon joule heating, was used for a variable-stiffness catheter⁵. With a similar technique, Field's metal alloy with a relatively low melting temperature (62°C), low viscosity in the liquid state, and high stiffness in the solid state was used to develop a continuum manipulator¹. Joule heating and water cooling are applied for transitioning the phases. While the heating time is only 3 s, cooling takes up to a minute.

Compared to structure-based designs, those based on phase-changing materials are structurally simpler with less small parts involved and have higher stiffness-changing ratios. Yet, there are several inherent drawbacks like long activation time, high applied voltages and currents, high transition temperature, and low stiffness in rigid states^{17, 20}. To address these concerns, it is important to choose suitable materials, stimulation methods, and designs that can offer high stiffness-changing ratio, short activation time, compact dimensions, and safe operation.

This paper presents a novel variable-stiffness continuum robotic manipulator using thermoplastic tubes, [Polyethylene Terephthalate](#) (PET), whose stiffness can be significantly adjusted through temperature. Joule heat is generated by applying electric current into the flexible stainless-steel coiled sheaths which are embedded inside the PET tubes. The robotic manipulator is covered with a thermal insulation layer made of Aerogel material to prevent thermal damage to surrounding tissue. An active air-cooling mechanism was employed to cool down the heated robotic manipulator by utilizing the inner channels of the PET tubes for air circulation. Using material-based approach for variable-stiffness has been report in¹⁷. However, active cooling has not yet been incorporated and understood. The contributions of this study are as follows: (1) Design and development of a variable-stiffness continuum manipulator with active heating and cooling; With an compact active cooling mechanism, the time for a complete stiffness-adjustment cycle is significantly shortened, which makes the technology more feasible in surgery; (2) characterization and modeling on the heating and cooling process, which are important for the control and optimization design of the manipulator.

2. Materials and Methods

2.1. Variable-stiffness robotic manipulator design

A schematic view of the robotic manipulator is given in Fig. 1. The robotic manipulator consists of a single continuum backbone made of a superelastic nitinol tube, 12 spacer disks with the distance of 10 mm, eight stainless steel tendons, and four variable-stiffness PET tubes. Actuated by eight cables in total (four cables for each section) located in the guiding pinholes on the spacer disks which are fixed on the backbone, the robot has two independently bending sections (Fig. 1c). To completely decouple the motions of the two bending sections, the tendons for the second segment are run through four flexible sheaths and converge close to the center of the first segment (Fig. 1c). The sheaths apply

counterbalanced forces (equal to the tension on the tendons) to the first spacer disk of the second bending section so that the first bending section would not bend when the second section is actuated ^{16, 19}. The prototype is shown in Fig. 1d.

The stiffness of the structure mostly relies on the flexible backbone and the four PET tubes running along the robot's body. Inside each PET tube, there is a flexible stainless steel sheath working as the heating element (Fig. 2). By applying electric current into the sheaths, resistive heat will be generated due to the electrical resistance of the coiled sheath and transferred to the PET tubes. If the temperature is below the transition threshold (around 67°C-70°C), PET will stay in the stiff glass state. Once the temperature reaches the threshold, the tubes will transform from glassy to rubbery state. The flexural modulus of PET material is 2.41-3.1 GPa and 82-124 MPa in the glass and rubber state, respectively ¹⁷.

After being heated up, the robot needs to be cooled down when high stiffness is needed. Active cooling can help remove the heat from the PET tube away faster than ambient cooling. A number of active cooling approaches that have been studied for shape memory alloy is also applicable to the proposed system ²⁶. While liquids (e.g., water) are fast for cooling, cool air is chosen for the electrical safety. The inner channels of the PET tubes are also utilized as the cooling channels for the air. A pair of tubes are connected at the distal end to form the air circulation vessels; one is for the inlet and the other the outlet (Fig. 1e).

TABLE I
THE DIMENSIONS OF MAJOR COMPONENTS

Component	Dimension
Length	140 mm
Overall diameter	15 mm
Disk's OD	14 mm
Disk's width	2 mm
Backbone diameter	0.9 mm
Aerogel thickness	0.5 mm
Pinholes diameter	0.5 mm
Tendon diameter	0.42 mm
PET tubes' OD/ID	2.26 mm/1.35 mm
Sheath's OD	1.34 mm/0.9 mm

Previous studies recommended that the external diameter of the endoscopic devices should be within 15 mm ³. Thus, we chose the outer diameter of the disk to be 14 mm, the width of the disk equal 2mm, and a thermal insulation layer (made of Aerogel) with a thickness of 0.5 mm, which results in a robotic manipulator with the diameter of 15 mm. The detailed dimensions are given in Table I. Although these dimensions were rationally selected

based on space constraints, available commercial materials, and functional requirements, they are not fully optimized because the focus of the study is to test the concepts of changing the stiffness of the robotic manipulator using PET material and the heating and cooling mechanisms.

2.2. Variable stiffness characterization and validation

This section presents the three-point bending tests that were carried on to characterize the variable stiffness of the given design.

2.2.1. Variable stiffness characterization

The experiment set up is shown in Fig. 3a. The support span was set at 80 mm for all the tests. The samples were loaded at the speed of 5 mm/min until 5 mm deflection was reached. The force and displacements were recorded. In order to test robot's performance under multiple heating and cooling cycles, the experiment procedure has four steps as followed: (1) heat up the robot to transform PET from glass to rubbery state, (2) start the bending process and collect the data for the flexible state, (3) release the bending force and cool down the robot to transform PET from rubbery to glass state, (4) start the bending process and collect the data for the rigid state. These four steps are then repeated three times.

2.2.2. Variable stiffness validation

For navigation in the human body, the endoscope needs to be flexible to adapt to the tortuous path of the gastrointestinal tract. When the endoscopic instruments (e.g., graspers, endoloops) are working on the target tissue, the endoscope needs to be stiff enough to provide a strong platform. In this case, the most critical loading scenario is when a transverse force is applied to the tip. This transverse force can significantly bend the tip and thus deviate the endoscope from the desired orientation. In this section, experiments were conducted to see how the robot reacts to external transverse loading at the rigid or flexible states.

The experiment set up is shown in Fig. 4. The robot was placed on top of a black panel, and an endoscopic grasper was placed inside one of the endoscope tool channels with its end-effector reaching out of the endoscope tip. A tendon (with weight on the other end) was fixed to the grasper so that a transverse force can be applied to the grasper. To track the robot's shape, a set of white markers was painted on the black insulation sheet. The shape of the robot can be captured by a camera through these white markers. A checkerboard was used for the calibration of the camera.

The procedure has four main steps, described as bellow:

Step 1: Bend the robot to make an S-shape (the original shape).

Step 2: Take a photo of the original shape.

Step 3: Apply a transverse force to the distal end.

Step 4: Take a photo of the final shape.

The color images are converted to binary images using the green channel of original RGB form with a threshold of 180. The binary images contain the checkerboards, from which the rotation matrix and translation vector from checkerboard to the camera are calculated using the Matlab function “extrinsics.” After that, the Matlab function “pointsToWorld” calculates the coordinates of pixels in “the target dots” from the final images.

Three different scenarios, the robot without PET tubes, the robot with PET tubes in the glass state, and the robot with PET tubes in the rubbery state, were tested. Besides, two various force magnitudes (1 N, and 3.5 N), which are in the force range of surgical tasks ^{3, 4}, were selected. To get both qualitative and quantitative comparisons, the average distance error is measured based on the markers’ coordinates (1).

$$e = \frac{1}{N} \sum_{n=1}^N \sqrt{(x_c - x_i)^2 + (y_c - y_i)^2} \quad (1)$$

where N is the number of markers (N = 14 in this case); x_c , y_c , and x_i , y_i denote the coordinates in the changed and initial shape respectively. With different combinations of robot's configurations and forces, 4 cases were investigated.

2.3. Heating and cooling experiments

In the current design, resistive heating is achieved by applying an electrical current to the flexible stainless steel sheaths embedded inside the PET tube (Fig. 2). Heat is generated and transferred into the PET tube, followed by the phase change of PET once the temperature reaches the glass transition temperature. For cooling, cool air is circulated inside the circulation channels. Experiments were conducted to test the heating and cooling processes on the robotic manipulator.

The robotic manipulator with thermal sensors (model TH100PT, Thorlabs Inc., United State) is shown in Fig. 5a and the diagram of the experimental setup in Fig. 5b. Air from the pump passes through a tube that is dipped into iced water to create cold air. An airflow gauge was used at the inlet of the PET channels to measure the flow rate of the air, followed by a thermal sensor 1 which measures the temperature of the cooling air. Thermal sensor 2 is put on the PET tube surface (see Fig. 1), and the thermal sensor 3 is to measure the temperature outside the insulation layer.

The first study is to investigate the effect of different currents on heating time and ambient cooling time. Three different currents (0.2A, 0.3A, and 0.4A) are chosen. Considering the transition temperature of PET material is around 67°C-70°C and the overshoot, the current was turned off when the temperature of the PET tubes raised to 60°C in the heating phase, and the cooling was stopped once the PET temperature drops to 60°C in the cooling phase. To accelerate the cooling speed, ambient cooling was replaced by forced convective cooling using cold air at 13°C.

2.4. Heating and cooling models

It is highly desirable to understand how the temperature can be affected by the heating

and cooling systems so that future work on the optimal design and control can be further conducted for improved performances. This section describes a framework on the modeling of the heating and cooling process by employing simplified heat transfer models and the experimental data. Specifically, we aim to model how the temperature profile is affected by the heating current, air cooling velocity, and time.

In the current design, the heat generated from the stainless steel sheath is transferred to the internal parts inside the robot, which is the conduction phenomenon. Apart from that, heat is partially dissipated to the surrounding environment and taken away by the air cooling, producing convection process. To reduce the computational costs, an approach that integrates the simplified heat transfer model and the experimental data is proposed. Two different scenarios are investigated, one is with only ambient cooling and the other with active air cooling. Each scenario consists of three separate phases: heating, overshoot, and cooling.

2.4.1. Heating and ambient cooling models

To simplify the model, the robot was considered as a whole entity. For that reason, the conduction happening inside the robot is ignored. According to the conservation of energy principle, (2) defines the heating stage:

$$\begin{aligned} dQ &= dQ_{in} - dQ_{out} \\ \Leftrightarrow RI^2 dt - h_{am} A_{am} (T - T_{\infty}) dt &= mcdT \end{aligned} \quad (2)$$

where dQ – the change in the total energy of the system; dQ_{in} - the total energy entering the system; dQ_{out} - the total energy leaving the system; R - the sheath resistance; I - the applied current; h_{am} and A_{am} - the convective heat transfer coefficient and the surface area; T and T_{∞} - the temperature of the robot and environment respectively; m and c - the weight and specific heat of the robot.

Equation (2) yields the heating solution as (3); (4) is used instead of (3) for calculation and presentation purposes.

$$T = T_{\infty} + \frac{\beta I^2}{\alpha} (1 - e^{-\alpha t}) \quad t \in [0; t_h] \quad (3)$$

$$T = T_{\infty} + k_{11} I^2 (1 - e^{-k_{12} t}) \quad t \in [0; t_h] \quad (4)$$

where $\alpha = \frac{h_{am} A_{am}}{mc}$ and $\beta = \frac{R}{mc}$; t_h - the heating time (the moment of turning off the current); k_{11} and k_{12} are both constant.

During the experiments, authors experienced the overshoot phenomenon when the temperature of the PET tubes still keep raising for a while after turning off the power supply. This was due to an induced transient current caused by a sudden change of state²². Equation (5) describes the mentioned current in the overshoot phase.

$$I = I_0 e^{-\gamma t} \quad (5)$$

where I_0 – the magnitude of the electric current; γ - a constant of transient current.

Substituting (5) into (2), we obtain the overshoot as (6). Solving (6) gives us the solution (7).

$$RI_0^2 e^{-2\gamma t} dt - h_{am1} A_{am1} (T - T_\infty) dt = mcdT \quad (6)$$

$$T = T_\infty + e^{-\alpha_1 t} \left(\frac{\beta_1 I_0^2}{\alpha_1 - \gamma_1} e^{-(\gamma_1 - \alpha_1)t} + c \right) \quad (7)$$

where $\beta_1 = \frac{R}{mc}$; $\alpha_1 = \frac{h_{am1} A_{am1}}{mc}$; $\gamma_1 = 2\gamma$; c is the constant defined by the initial conditions.

For the ease of calculation and presentation, (8) will be used.

$$T = T_i + k_{21} I^2 e^{-k_{22}(t-t_h)} (1 - e^{-k_{23}(t-t_h)}) \quad t \in [t_h; t_o] \quad (8)$$

Here k_{21} , k_{22} , and k_{23} are all constant; t_h -the heating time; t_o -the end of overshoot (the moment temperature reaches the maximum).

Finally, the ambient convective cooling process takes place. Cancelling out the generated heat term in (2) gives us the following ambient cooling (9) and the solution (10).

$$-h_{am2} A_{am2} (T - T_\infty) dt = mcdT \quad (9)$$

$$T = T_\infty + (T_{i2} - T_\infty) e^{-\alpha_2 t} \quad (10)$$

where $\alpha_2 = \frac{h_{am2} A_{am2}}{mc}$; T_{i2} - the initial temperature of the cooling step (the maximum value).

For the ease of calculation and presentation, Equation in the form of (11) will be used.

$$T = T_\infty + (T_{i2} - T_\infty) e^{-k_{31}(t-t_o)} \quad t \in [t_o; t_e] \quad (11)$$

Here t_o -the end of overshoot (the start of the cooling process); t_e -the end of the cooling stage; k_{31} is a constant.

2.4.2. Heating and active air cooling models

The same procedure is carried out in order to build the model in the case of active air cooling. Although, the term “active air” is used, but the ambient cooling is always happening. The heating solution is the same as (3). For differentiation and presentation, other notations are employed as (12) and (13).

$$T = T_\infty + \frac{\beta_a I^2}{\alpha_a} (1 - e^{-\alpha_a t}) \quad (12)$$

$$T = T_{\infty} + k_{41}I^2(1 - e^{-k_{42}t}) \quad t \in [0; t_h] \quad (13)$$

where $\alpha_a = \frac{h_{ama}A_{ama}}{mc}$ and $\beta_a = \frac{R}{mc}$; k_{41} and k_{42} are constant.

Cold air is pumped in simultaneously with turning off the current. For this reason, the overshoot (14) is unlike the ambient case.

$$\begin{aligned} RI_0^2 e^{-2\gamma_a t} dt - h_{ama1}A_{ama1}(T - T_{\infty}) \\ .dt - h_{a1}A_{a1}(T - T_a)dt = mcdT \end{aligned} \quad (14)$$

where T_a - the temperature of cold air; h_{a1} and A_{a1} - the convective heat transfer coefficient and the contact surface area.

Solving the (14) provides us the solution (15) or (16).

$$T = \frac{\tau_{a1}}{\alpha_{a1}} + e^{-\alpha_{a1}t} \left(\frac{\beta_{a1}I^2}{\alpha_{a1} - \gamma_{a1}} e^{-(\gamma_{a1} - \alpha_{a1})t} + c \right) \quad (15)$$

$$\begin{aligned} T = T_{ai1} + \frac{k_{52}}{k_{51}}(1 - e^{-k_{51}(t-t_h)}) \\ . + k_{54}I^2 e^{-k_{51}(t-t_h)}(1 - e^{-k_{53}(t-t_h)}) \end{aligned} \quad (16)$$

$$t \in [t_h; t_o]$$

where $\alpha_{a1} = \frac{h_{ama1}A_{ama1} + h_{a1}A_{a1}}{mc}$; $\beta_{a1} = \frac{R}{mc}$; $\tau_{a1} = \frac{h_{ama1}A_{ama1}T_{\infty} + h_{a1}A_{a1}T_a}{mc}$; $\gamma_{a1} = 2\gamma_a$; T_{ai1} - the initial temperature when the overshoot starts; c-constant defined by initial conditions. Here k_{51} , k_{52} , k_{53} , and k_{54} are all constant. Because the air convective heat transfer coefficient h_{a1} is proportional to the velocity v ¹⁵, the terms α_{a1} and τ_{a1} can be rewritten as (17) for the calculation purpose.

$$\begin{cases} k_{51} = \alpha_{a1} = x_{\alpha 1} + y_{\alpha 1}v \\ k_{52} = \tau_{a1} = x_{\tau 1} + y_{\tau 1}v \end{cases} \quad (17)$$

Lastly, the active convective cooling process takes place. Canceling out the generated heat term in (14) gives us the following active cooling as (18) and the solution (19) or (20).

$$-h_{ama2}A_{ama2}(T - T_{\infty})dt - h_{a2}A_{a2}(T - T_a)dt = mcdT \quad (18)$$

$$T = \frac{\tau_{a2}}{\alpha_{a2}} + \left(T_{ai2} - \frac{\tau_{a2}}{\alpha_{a2}} \right) e^{-\alpha_{a2}t} \quad (19)$$

$$T = k_{61} + (T_{ai2} - k_{61})e^{-k_{62}(t-t_o)} \quad t \in [t_o; t_e] \quad (20)$$

where $\alpha_{a2} = \frac{h_{ama2}A_{ama2} + h_{a2}A_{a2}}{mc}$; $\tau_{a2} = \frac{h_{ama2}A_{ama2}T_{\infty} + h_{a2}A_{a2}T_a}{mc}$; T_{ai2} - the initial temperature of the cooling step (the maximum value). Here t_o - the end of overshoot (the start of the cooling process); t_e - the end of the cooling stage; k_{61} and k_{62} are constant.

Similarly, α_{a2} , τ_{a2} , k_{61} , and k_{62} can be simplified as (21).

$$\begin{cases} k_{61} = \alpha_{a2} = x_{\alpha2} + y_{\alpha2}v \\ k_{62} = \tau_{a2} = x_{\tau2} + y_{\tau2}v \end{cases} \quad (21)$$

3. Results

3.1. Three-point bending results

Based on the collected force and deflection (plotted in Fig. 3b), the stiffness, which is the ratio of the force to the deflection, of the manipulator in glass state and rubber state are calculated and equal to 4.4 N/mm and 0.2 N/mm, respectively. The stiffness ratio between the two states is 22.0. This stiffness variation ratio is much higher than that of the CF-240AL endoscope (Olympus, Japan) whose stiffness ratio is only about 1.59. In terms of flexural rigidity, the mentioned endoscope (the bending section) in the flexible mode has the smallest flexural rigidity of 103.74 Ncm²; in the rigid state, it holds the maximum flexural rigidity of 164.84 Ncm² ^{3, 28}. However, the rigidities of the proposed manipulator are 469.33 Ncm² and 21.33 Ncm² in the stiff and compliant modes, respectively. This means the proposed manipulator is almost three times stiffer than the state-of-the-art variable-stiffness endoscope in the stiff mode and meanwhile five times more flexible than the latter in the flexible mode. Thus, in the stiff mode, although the proposed manipulator would still be deflected under external loads, the deflection is expected to be three times smaller than the state-of-the-art variable-stiffness endoscope. Note that the flexural rigidity of the robotic manipulator is also estimated using the formula $EI = \frac{FL^3}{48\delta}$, in which, the production of EI represents the flexural rigidity, F - the bending force, L - the support span distance, δ - the displacement. In addition, the bending results show the performance repeatability after multiple heating and cooling cycles.

3.2. Variable stiffness verification

In the first two cases, i.e., the robot without PET tubes and the robot with PET tubes in rubbery state, the distal end was pulled by weight with the force equal to 1 N while the actuation cable tensions were kept at 5 N. After reconstruction, the marker points are plotted in Fig. 6a and Fig. 6b, and the average distance errors are estimated ($e_1 = 33.61$ mm, $e_2 = 33.31$ mm).

The robot with embedded PET tubes in the glass state was exerted with 1 N, and 3.5 N forces in the other three cases (no tension on other cables). The results are shown in Fig. 6c and Fig. 6d. Similar to the previous cases, the average distance errors are computed with the formula in (1) ($e_3 = 3.63$ mm, $e_4 = 8.36$ mm).

3.3. Heating and cooling results

Fig. 7a, which plots the temperature versus time, indicates that higher current produces faster heating speed, while ambient cooling takes quite a long time. For example, it costs 15s and 7.5s to reach 60°C with 0.3A and 0.4A respectively. The ambient cooling time is longer in the case of higher applied current because the peak temperature is higher. For instance, the ambient cooling times for 0.2A, 0.3A, and 0.4A are 36.1s, 100.3s, and 184.1s respectively.

As seen in Fig. 7b, which depicts the PET tube's temperature versus time, overshoot and cooling time are vastly shortened in comparison with ambient cooling. In particular, for the case of 0.3A electric current, the overshoot duration was reduced from 12.3s to 4.8s (60% less) and cooling was shortened from 100.3s to 11.9s (almost 10 times faster). Also, faster airspeed resulted in shorter overshoot and cooling duration. For example, overshoot and cooling times are 6.91s and 16.6s when using 0.04 L/s air flow rate, while those of 0.05 L/s are 6.39s and 14.54s and those of 0.06 L/s are 4.85s and 11.96s.

It is also important to notice that the temperatures on the thermal insulation surface stay below 35 °C during the experiments (Fig. 7c) which is in the safety range for the human body (≤ 41 °C³).

3.4. Heating and cooling model verification

In order to tune the coefficients in the abovementioned models, the Curve Fitting Toolbox and the command *lsqcurvefit* inside the MATLAB are utilized.

TABLE II
THE VALUES OF COEFFICIENTS OF THE MODELS

Model	Data sets used for parameter identification	Data sets used for model verification	Results
(4)	Am ($I = 0.2 A$)	Am ($I = 0.3A, 0.4A$)	$T_{\infty} = 23.5; k_{12} = 0.006; k_{11} = 6338.975$
(8)	Am ($I = 0.4A$)	Am ($I = 0.2A, 0.3A$)	$k_{21} = 1622.047; k_{22} = 0.071; k_{23} = 0.027$
(11)	Am ($I = 0.2A$)	Am ($I = 0.3A, 0.4A$)	$T_{\infty} = 23.5; k_{31} = 0.045$
(13)	Am ($I = 0.2 A$)	Ac ($I = 0.3 A$)	$T_{\infty} = 23.5; k_{42} = 0.006; k_{41} = 6338.975$
(16)	Ac ($f \frac{0.04L}{s}, \frac{0.06L}{s}$)	Ac ($f \frac{0.05L}{s}$)	$x_{\alpha 1} = 0.026; y_{\alpha 1} = 0.215; x_{\tau 1} = 0.066; y_{\tau 1} = 0.012; k_{53} = 0.1734; k_{54} = 183.16$
(20)	Ac ($f \frac{0.04L}{s}, \frac{0.06L}{s}$)	Ac ($f = \frac{0.05L}{s}$)	$x_{\alpha 2} = 0.4; y_{\alpha 2} = 9.98; x_{\tau 2} = 0.215; y_{\tau 2} = 0.0128$

Here, “Am” refers to the case of heating and ambient cooling; “Ac” is considered as the instance of heating and active air cooling.

There are six models ((4) (8) (11) (13) (16) (20)), which are equally divided into two scenarios, with three major variables including time- t , current- I , and the air velocity- v . Two of them require two data sets to define coefficients ((16) (20)), while the rest needs only one data set. The reason for that is because the relationships between the velocity variable (v) and the coefficients k_{51} , k_{52} , k_{61} , and k_{62} can only be solved with two pairs of known coefficients ((17) (21)). Table II summarizes the values of the coefficients after the identification and verification processes.

Fig. 8 depicts the results of the developed models and the experiment data for the qualitative comparison, while Table III summarizes the Root Mean Square Errors (RMSE) for the quantitative comparison.

TABLE III
ROOT MEAN SQUARE ERRORS OF THE MODELS

Case	Current/Air velocity	Root mean square errors
Heating and ambient cooling	$I = 0.2A$	$0.7504\text{ }^{\circ}C$
	$I = 0.3A$	$0.7984\text{ }^{\circ}C$
	$I = 0.4A$	$1.3066\text{ }^{\circ}C$
Heating and active cooling	$f=0.04L/s$	$0.8465\text{ }^{\circ}C$
	$f=0.05L/s$	$0.5790\text{ }^{\circ}C$
	$f=0.06L/s$	$0.6799\text{ }^{\circ}C$

4. Discussion

Based on the 3-point bending experiment results, It can be seen that the proposed scope is much stiffer than the Olympus endoscope in rigidified mode, while it's also much more flexible than the Olympus endoscope in compliant mode. In short, the proposed manipulator has improved stiffness and flexibility in the two modes (rigid and flexible modes) when compared with the commercial variable-stiffness endoscope, and the former exhibits a significantly higher stiffness-changing ratio (22) than the latter (1.59). The Table IV below summarizes the performances of several variable-stiffness devices available on the literature. In quantitative comparison with structure-based devices, the proposed design outperforms several ones in terms of stiffness²⁹ or stiffness ratio⁹. In particular, the slider linkage lock mechanism²⁹ can bear only 0.1N for the third joint, while the experiments show that the our robot has very small displacement with 1N force applied. Moreover, the proposed manipulator yields high stiffness ratio (22) between two states, while that of STIFF-FLOP module⁹ is only 1.36. When comparing with other material-based devices, the studied one has better activation time and stiffness ratio. For example, the activation time of the proposed robot is 30s, while that of the continuum manipulator 1 is up to 63s. Furthermore, the

platform for single site surgery ¹⁸ has the stiffness variation of 4, while ours is up to 22.

TABLE IV: THE PERFORMANCE COMPARISONS OF SEVERAL VARIABLE-STIFFNESS MANIPULATORS.

Approach	Activation Time	Stiffness in rigid state	Stiffness in compliant state	Stiffness ratio	Reference
Structure-based	No data (short in principle)	The third joint can bear only 10gf (0.1N) with 400kPa pressure	No data	No data	29
	No data (short in principle)	0.529 N/mm with 59.9N cable tension	No data	No data	14
	No data (short in principle)	1489 Ncm ²	No data	No data	21
	No data (short in principle)	No data	No data	36% increase	9
Material-based	37s	0.23N/mm	0.056N/mm	4	18
	63s	No data	No data	No data	1
	No data (long in principle)	No data	No data	No data	5
Proposed Design	30s	469.33 Ncm ²	21.33 Ncm ²	22	

Regarding the variable stiffness validation, with the consideration of the above graphs and measured average distance errors, several conclusions can be made. Firstly, the cable tension has less impact on holding the robot's shape (huge e_1) due to the under-actuation feature (the number of motors is less than the degrees of freedom of the robot manipulator). Secondly, while PET tubes are compliant in the rubbery state ($e_1 \approx e_2$), the robot can be significantly stiffened thanks to the PET tubes in the glass state (much smaller e_3 compared to e_1). The validation study confirms that the robot has smaller unwanted deflection (8.36mm) under typical transverse force in NOTE (3.5N) while still be highly flexible in the flexible mode.

The heating and cooling measurements show that the higher the cooling airspeed, the shorter the overshoot and cooling time. Based on our experience on flexible endoscopy ^{4, 24}, the activation time, in particular, 12 s for cooling, is sufficient. This can be understood from the detailed operation procedures of the robotic flexible endoscopic procedure: (1), the endoscope is inserted to the surgical site, and this insertion process is normally slow and takes more than 10 minutes. In this process, the endoscope should be in the flexible mode which can be achieved within 7.5-15 seconds with the proposed heating mechanism; (2) once the endoscope arrives at the surgical cite, robotic/manual instruments are inserted through the tool channels of the endoscope, which takes around 2~3 minutes or longer; during this time

period, the endoscope can be cooled down to become stiff in around 12 seconds. Note that, during robotic endoscopic surgery, the robotic instruments inside the endoscope tool channels move frequently but the endoscope itself does not move much because it needs to serve as the stable platform of the robotic instruments; the surgeon may need to move the endoscope from one site to the other (not frequent), and this normally involves further manoeuvres of the endoscope which can take several minutes; thus, it is quite affordable to allow 12 seconds to adjust the stiffness. Moreover, the models can accurately predict the heating and cooling temperatures with small RMSE. Lastly, the thermal insulation layer makes the design more applicable to the human body in terms of safety.

The results confirm the feasibility of building a compact, variable-stiffness endoscopic manipulator with significantly high stiffness-changing ratio, shortened time for switching the modes, and safe thermal insulation. The proposed variable-stiffness manipulator may be applied for flexible endoscopes in general flexible endoscopy and key-hole surgery.

While variable-stiffness approach can be effective for more accurate surgery, it is also important to study and control both the tip force and the stiffness for safe operation^{7,12}. One limitation of the current study is that the real-time control of temperature or stiffness is not implemented; our next important step would be to develop the schemes for temperature/stiffness control. Optimal designs also need to be pursued by considering the trade-offs among conflicting requirements and constraints such as sizes, overall stiffness and flexibility, heating and cooling durations. The derived models will be used to improve the robot performance and design the control scheme. Finally, the manipulator needs to be tested and evaluated in more realistic surgical scenarios (ex vivo or in vivo endoscopic procedures) in terms of stiffness, activation time, unwanted deflection, and the improvement it brings to the operators. We have confirmed the feasibility of the proposed concepts through bench-top tests, e.g., stiffness adjustment, heating and cooling, and heat isolation, in a manipulator designed with reasonable size constraints. However, a complete functioning endoscope with embedded cameras and electronics should be developed and then tested in-vivo extensively before the technology can be applied clinically.

Acknowledgements

This research was supported by the National Research Foundation (NRF) Singapore through the NRF Investigatorship grant (NRFI2016-07).

References

1. Alambeigi F., R. Seifabadi and M. Armand. A continuum manipulator with phase changing alloy. In: *2016 IEEE International Conference on Robotics and Automation (ICRA)2016*, p. 758-764.
2. Beasley R. A. Medical Robots: Current Systems and Research Directions. *Journal of Robotics* 2012: 14, 2012.
3. Blanc L., A. Delchambre and P. Lambert. Flexible Medical Devices: Review of Controllable Stiffness Solutions. *Actuators* 6: 23, 2017.

4. Cao L., X. Li, P. T. Phan, A. Tiong, J. Liu and S. Phee. *A Novel Robotic Suturing System for Flexible Endoscopic Surgery*. 2019.
5. Chautems C., A. Tonazzini, D. Floreano and B. J. Nelson. A variable stiffness catheter controlled with an external magnetic field. In: *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)2017*, p. 181-186.
6. Chenal T. P., J. C. Case, J. Paik and R. K. Kramer. Variable stiffness fabrics with embedded shape memory materials for wearable applications. In: *Intelligent Robots and Systems (IROS 2014), 2014 IEEE/RSJ International Conference onIEEE*, 2014, p. 2827-2831.
7. Cheng W. B., Y. Y. Di, E. M. Zhang, M. A. Moser, S. Kanagaratnam, L. Y. Korman, N. Sarvazyan and W. J. Zhang. Modeling and in vitro experimental validation for kinetics of the colonoscope in colonoscopy. *Annals of Biomedical Engineering* 41: 1084-1093, 2013.
8. Cheng W. B., M. A. Moser, S. Kanagaratnam and W. J. Zhang. Overview of upcoming advances in colonoscopy. *Dig Endosc* 24: 1-6, 2012.
9. Cianchetti M., T. Ranzani, G. Gerboni, I. De Falco, C. Laschi and A. Menciassi. STIFF-FLOP surgical manipulator: Mechanical design and experimental characterization of the single module. In: *Intelligent Robots and Systems (IROS), 2013 IEEE/RSJ International Conference on2013*, p. 3576-3581.
10. De Falco I., M. Cianchetti and A. Menciassi. A soft multi-module manipulator with variable stiffness for minimally invasive surgery. *Bioinspir Biomim* 12: 056008, 2017.
11. Degani A., H. Choset, A. Wolf and M. Zenati. Highly articulated robotic probe for minimally invasive surgery. In: *Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference onIEEE*, 2006, p. 4167-4172.
12. Hu X., L. Cao, Y. Luo, A. Chen, E. Zhang and W. J. Zhang. A Novel Methodology for Comprehensive Modeling of the Kinetic Behavior of Steerable Catheters. *IEEE/ASME Transactions on Mechatronics* 24: 1785-1797, 2019.
13. Hu X. and A. Chen. Steerable catheters for minimally invasive surgery: a review and future directions. 23: 21-41, 2018.
14. Kim Y., S. Cheng, S. Kim and K. Iagnemma. A Stiffness-Adjustable Hyperredundant Manipulator Using a Variable Neutral-Line Mechanism for Minimally Invasive Surgery. *Ieee Transactions on Robotics* 30: 382-395, 2014.
15. Kreith F., R. M. Manglik and M. S. Bohn. *Principles of heat transfer*. Cengage learning, 2012.
16. Lai W., L. Cao, Z. Xu, P. T. Phan, P. Shum and S. J. Phee. Distal End Force Sensing with Optical Fiber Bragg Gratings for Tendon-Sheath Mechanisms in Flexible Endoscopic Robots. In: *2018 IEEE International Conference on Robotics and Automation (ICRA)2018*, p. 1-5.
17. Le H. M., L. Cao, T. N. Do and S. J. Phee. Design and modelling of a variable stiffness manipulator for surgical robots. *Mechatronics* 53: 109-123, 2018.
18. Li J., X. Li, J. Wang, Y. Xing, S. Wang and X. Ren. Design and evaluation of a variable stiffness manual operating platform for laparoendoscopic single site surgery (LESS). *The International Journal of Medical Robotics and Computer Assisted Surgery* e1797-n/a, 2017.

19. Li X., L. Cao, A. M. H. Tiong, P. T. Phan and S. J. Phee. Distal-end force prediction of tendon-sheath mechanisms for flexible endoscopic surgical robots using deep learning. *Mechanism and Machine Theory* 134: 323-337, 2019.
20. Loeve A., P. Breedveld and J. Dankelman. Scopes too flexible...and too stiff. *IEEE Pulse* 1: 26-41, 2010.
21. Loeve A. J., D. H. Plettenburg, P. Breedveld and J. Dankelman. Endoscope shaft-rigidity control mechanism: "FORGUIDE". *IEEE Trans Biomed Eng* 59: 542-551, 2012.
22. Nilsson J. W. and S. A. Riedel. *Electric Circuits*. Prentice Hall Professional Technical Reference, 1999, p. 1030.
23. Olson G. Medical devices with variable stiffness. Google Patents, 2013.
24. Phee S. J., N. Reddy, P. W. Y. Chiu, P. Rebala, G. V. Rao, Z. Wang, Z. Sun, J. Y. Y. Wong and K. Y. Ho. Robot-Assisted Endoscopic Submucosal Dissection Is Effective in Treating Patients With Early-Stage Gastric Neoplasia. *Clinical Gastroenterology and Hepatology* 10: 1117-1121, 2012.
25. Rattner D. and A. Kalloo. ASGE/SAGES Working Group on Natural Orifice Translumenal Endoscopic Surgery. October 2005. *Surgical Endoscopy* 20: 329-333, 2006.
26. Tadesse Y., N. Thayer and S. Priya. Tailoring the Response Time of Shape Memory Alloy Wires through Active Cooling and Pre-stress. *Journal of Intelligent Material Systems and Structures* 21: 19-40, 2010.
27. Vitiello V., S. L. Lee, T. P. Cundy and G. Z. Yang. Emerging robotic platforms for minimally invasive surgery. *IEEE Rev Biomed Eng* 6: 111-126, 2013.
28. Wehrmeyer J. A., J. A. Barthel, J. P. Roth and T. Saifuddin. Colonoscope flexural rigidity measurement. *Medical & Biological Engineering & Computing* 36: 475-479, 1998.
29. Yagi A., K. Matsumiya, K. Masamune, H. Liao and T. Dohi. Rigid-Flexible Outer Sheath Model Using Slider Linkage Locking Mechanism and Air Pressure for Endoscopic Surgery. Berlin, Heidelberg: Springer Berlin Heidelberg, 2006, p. 503-510.
30. Yalcintas M. and H. Dai. Magnetorheological and electrorheological materials in adaptive structures and their performance comparison. *Smart Materials and Structures* 8: 560, 1999.

Figures

Fig. 1. Robotic manipulator: (a) overview of the manipulator, (b) cross-section of the disk, (c) details of inner structures and components, (d) the prototype (white dots are shape-tracking markers used in experiments), (e) the cooling system including inlet, connecting, and outlet channels.

Fig. 2. The working principle of variable-stiffness PET tube.

Fig. 3. The 3-point bending experiment: (a) the experiment set up, (b) the force and displacement data.

Fig. 4. The validation experiment setup: (a) robot in the original shape, (b) robot in the changed shape after applying force F .

Fig. 5. Experiment setups: (a) the manipulator with temperature sensors, and (b) the diagram of the heating and cooling experiment setup. Sensors 1, 2, 3 are to measure the temperatures of the cooling air at the inlet, PET tubes inside the manipulator, and the outer surface of the insulation layer, respectively.

Fig. 6. The reconstructed dots along the robot body: (a) robot without PET tubes and applied 1N force, (b) robot with PET tubes in the rubbery state and applied 1N force, (c) robot with PET tubes in glass state and applied 1N force, (d) robot with PET tubes in glass state and applied 3.5N force.

Fig. 7. The temperature measured from thermal sensor. (a) The temperature outside the PET tube in the heating and cooling phases (data from thermal sensor 2), (b) The temperature outside the PET tube when heating with 0.3A current, air, and ambient cooling (data from thermal sensor 2), (c) The temperature outside the Aerogel surface in 3 different cases (data from thermal sensor 3).

Fig. 8. Experiment data and results from models, (a) ambient cooling, (b) active air cooling.