Tele-micromanipulation of Electrothermally Actuated Robotic Fibre for Precise Medical Applications

Jinshi Zhao, Yue Li, Mohamed E. M. K. Abdelaziz,
Bruno Gil Rosa, Libaihe Tian, Qindong Zheng and
Burak Temelkuran

October 23, 2024

Tele-micromanipulation of Electrothermally Actuated Robotic Fibre for Precise Medical Applications

Jinshi Zhao[1,2], Yue Li[2], Mohamed E. M. K. Abdelaziz[2], Bruno Gil Rosa[2], Libaihe Tian[1,2], Qindong Zheng[2], Burak Temelkuran[1*]
[1]*Department of Metabolism, Digestion and Reproduction, Imperial College London*
[2]*The Hamlyn Centre for Robotic Surgery, Imperial College London*
j.zhao19@imperial.ac.uk

INTRODUCTION

Surgical approaches for tumour resection aim to minimise the sacrifice of healthy tissue while ensuring complete removal of the tumours to avoid recurrence. This is particularly challenging in minimally invasive surgery (MIS). Miniaturized and precise robotic instruments that can manipulate diagnostic or therapeutic tools allow superior access and enhance the accuracy of these surgeries. In this context, several fibre-based robots have been developed [1,2].

In our previous work, we have developed an electrothermally actuated robotic fibre. The fibre's actuation is achieved by differential thermal expansion across the fibre's cross-section, induced by Joule heating (Fig. 1a). This robotic fibre enables the precise delivery and manipulation of surgical tools like laser fibres [3]. Our published work [3] has well-documented the analyses of its dynamic behaviour, mechanical, and thermal properties. The comparison with state-of-the-art actuators also highlights the contributions of our robot in terms of precision (<50μm), dimensions (<2mm), motion range (<6mm), maximum velocity (10.3mm/s), and simplicity of the actuation unit [3].

In this work, we developed a telemanipulation controller that allows the operator to control the robotic fibre with a joystick manually. To demonstrate and evaluate the motion precision of this robotic system, we designed a micro-manipulation task. We utilised the robotic fibre to hold and manipulate a bespoke electromagnet coil to grab and move a magnetic particle along a small maze with a tortuous path.

A longer fibre was designed and inserted through a da Vinci instrument to improve the precision of the surgery. Considering that only the fibre distal end needs to be actuated, a partial actuation approach would benefit the patient's safety and energy consumption. In the second part of this work, we introduce a new approach enabling actuation and control of the 12-centimetre distal end of a 1.2-metre-long fibre robot. The assembled robotic system was tested in an abdominal phantom, validating the concept of integrating robotic fibres with commercially available endoscopic devices.

MATERIALS AND METHODS

1. Micromanipulation Experimental Setup

The electromagnetic coil was fabricated by wrapping insulated copper wires (50μm in diameter) around an iron cylinder (6 mm in length and 1 mm in diameter). The resulting electromagnetic coil (diameter of 2.5 mm) was mounted on the robotic fibre. The terminals of the copper wire were threaded through the fibre's centre working channel and connected to a direct current power source. An auxiliary switch was incorporated to control the electromagnet's activation, enabling the pickup and release of the magnetic particle.

To evaluate the micromanipulator's performance, we built a vertically oriented experimental setup (Fig. 1b). The robotic assembly (Fig. 1c) was placed vertically, with the electromagnet pointing towards a water-filled Petri dish (Fig. 1d). A transparent paper sticker with a printed maze pattern was attached to the bottom of the Petri dish. Additionally, a digital microscope was placed below the Petri dish.

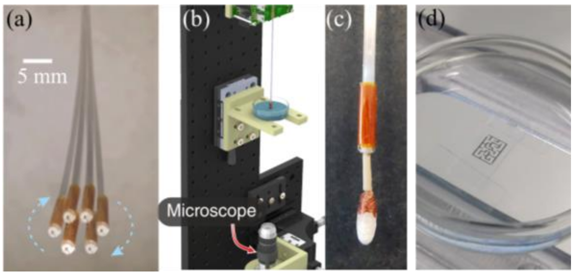

Fig. 1 Robotic fibre, electromagnet, and micro-manipulation experimental setup. (a) An overlapped image shows the robotic fibre moving along a circular path. (b) Schematics of the vertically oriented micro-manipulation setup. (c) The robotic fibre-electromagnet assembly. (d) The water-filled Petri dish with maze pattern transparent sticker on the bottom.

2. Tip-only Actuated Robotic Fibre Fabrication

The proposed robotic fibre was made of a polymer fibre with three sets of equidistantly spaced wires (copper, stainless steel, copper), each 50 μm in diameter. Partial actuation of the robotic fibre was achieved by concentrating electrical power on the distal 12 cm stainless-steel wires, leveraging the resistivity difference between the copper (resistivity $\rho = 1.68 \times 10^{-8}\ \Omega \cdot m$) and the stainless steel ($\rho = 7.4 \times 10^{-7}\ \Omega \cdot m$) wires. The circuit connection on the fibre is shown in Figure 2. During actuation, the electrical power per unit length of the stainless-steel wire is around 44 times of the copper wire. As a result, the stainless-steel wires serve as heating sources for fibre actuation, while the copper wires facilitate electricity transfer and remain cold.

For the circuit connection, we intertwined the stainless-steel wire with one of the copper wires at the distal end (Fig. 2). This was followed by exposing the same resistive stainless-steel wire and another conductive copper wire at a selected point along the length of the fibre by scraping away the polymeric encapsulation with a microtome blade. Subsequently, conductive silver paint was applied to the distal end and actuation point to ensure reliable electrical contact. The copper wires protruding from the robotic fibre's proximal end were soldered onto a printed circuit board (PCB) with a multiple-pin circuit adapter.

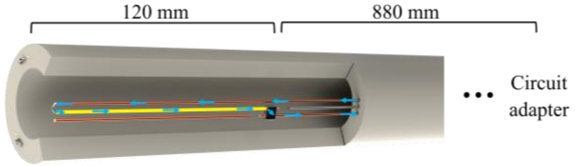

Fig. 2 Robotic fibre circuit connection.

3. Robotic Fibre Actuation and Control

The circuit adapter connects with the subsequent actuation unit (voltage amplifier circuit) and control unit (the digital-to-analogue converter docks on a real-time controller) through cables, enabling the remote delivery of actuation energy and control signals. The robot controller was built in the LabVIEW environment. To control the robot's motion, the motion direction of the fibre is defined into three areas. Based on the defined area, the control system powers the relevant wire(s) for actuation. The displacement of the fibre distal end is linearly proportional to the electrical power applied to the corresponding wire [3]. The contribution of each wire to the desired displacement is calculated using the component of their displacement vectors.

RESULTS

1. Particle Placement in Mazes

Figure 3a shows the microscope view of the maze pattern and the narrowest wall gap of 600 µm. A magnetic particle with a dimension of 600 µm was placed at the entrance of the maze (top left side in Figure 3a). The operator controlled the robot's motion with the joystick while watching the microscope monitor to see the component position in real-time.

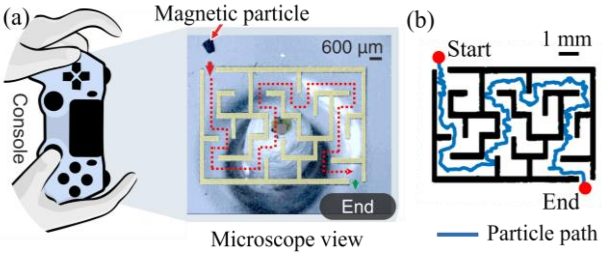

Fig. 3 The microscope view of the micro-manipulation along the maze pattern. (a) Schematics of using a joystick to control the robotic fibre-electromagnet. (b) The path of fibre manipulates the magnetic particle to move along the maze.

Initially, the operator controlled the robotic fibre to move to the maze entrance from the maze centre. Sequentially, the user turned on the power switch of the electromagnet to grab and move the magnetic particle along the maze. The particle was dropped after it was delivered to the end of the maze. With a new operator's manual control in this complicated and narrow path, the entire process took around 10 minutes, the average speed of the robot was around 3 mm/min, and the particle was always inside the maze wall (Fig. 3b).

2. Phantom Study with Tip-only Actuated fibre

To validate the partial actuation mechanism, we measured the temperature of an actuated fibre within an ambient temperature of approximately 25℃. The result presents a 26.5℃ difference between the actuated (52.6℃) and passive (26.1℃) sections of the fibre.

For the phantom study, we designed a bespoke 3D printed laparoscopic fibre holder to integrate the robotic fibre on the da Vinci® robotic system (Fig. 4a). Additionally, we passed an optical fibre, coupled with a red LED, through the robotic fibre central channel to simulate a surgical laser fibre. For demonstration, the da Vinci instrument delivered the robotic fibre into an abdomen phantom (Fig. 4b) and coarsely positioned the fibre tip near a simulated tumour area (black area). The operator telemanipulated the fibre to scan along the contour of tumour tissue (Fig. 4c). The entire scanning process took 4 minutes.

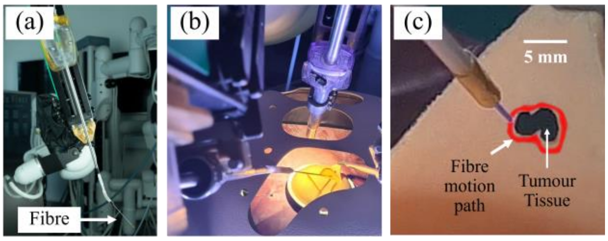

Fig. 4 Instrument integration and phantom demonstration. (a) The integration between the Da Vinci® surgical robot and the fibre actuator. (b) Experimental setup of abdominal phantom study. (c) A scan along the contour of a simulated tumour tissue with an embedded optical fibre.

DISCUSSION

The preliminary experiments demonstrate the precision of robotic fibre and its compatibility with commercially available surgical platforms, thus enabling the integration of multifunctional devices and improving access capabilities, helping surgeons work around margins with improved safety and confidence. Future work will focus on optimising the robotic fibre's scanning strategy to achieve faster and more automated surgical scans with enhanced precision. Additionally, we plan to functionalise our robotic fibre by combining it with multiple therapeutic (such as laser ablation) and diagnostic (morphological or molecular) devices. We are currently working on applying robotic fibre to improve precision, access, and visualisation in transoral and transvaginal surgeries, targeting surgeries that preserve healthy tissue and reduce recurrence rates.

REFERENCES

[1] A. Leber *et al.*, "Highly integrated multi-material fibers for Soft Robotics," *Advanced Science*, vol. 10, no. 2, 2022.

[2] C. Zhou *et al.*, "Ferromagnetic soft catheter robots for minimally invasive bioprinting," *Nature Communications*, vol. 12, no. 1, 2021.

[3] M. E. Abdelaziz, J. Zhao et al., "Fiberbots: Robotic fibers for high-precision minimally invasive surgery," *Science Advances*, vol. 10, no. 3, 2024.