# A Pop-Up Soft Robot Driven by Hydraulic Folded Actuators for Minimally Invasive Surgery

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# A Pop-Up Soft Robot Driven by Hydraulic Folded Actuators for Minimally Invasive Surgery

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## INTRODUCTION

The incidence rate of colorectal cancer ranks third among all cancers, which is a serious threat to human health [1]. Endoscopic submucosal dissection (ESD) is an effective endoscopic surgical method for early gastric and colorectal cancers. However, ESD is a procedure with high technical requirements, which brings a higher risk of complications and requires long training for clinicians [2].

Robots are expected to simplify ESD procedures and reduce training time. But there is no standard flexible robotic endoscope at present. Soft robots can potentially offer better adaptability and safer interaction with the environment. As such, they hold great potential in solving the technical challenges of the current minimally invasive surgery (MIS), which are difficult to be solved by rigid robots.

Here we demonstrate an inflatable robot which is largely made of flexible plastic film. In the deflated state, it is easy to collapse, fold and roll into a small size, promising easier delivery by a carrier endoscope mounted on its side to the proximal colon. After reaching the target site, the robot braces itself against the colon wall after inflation and then the surgery is performed. This work is based on the soft Cyclops robots which can deploy after inflation [3][4]. However, small folded hydraulic actuators are used to replace the contraction-based pouch actuators used in [4], which have a larger size. The anchor points of the cables with planar layout replace the spatial layout in [3], which reduces the axial size of the robot, allowing it to pass through the colon bends more easily. Folded actuators made of an airbag are flexible and adaptable [5]. The actuator volume is very small under deflated condition, but it can achieve large deformation after inflation. The proposed actuator uses a folded chamber to pull the cable to produce a large displacement without the need of displacement amplification mechanisms. In the deflated state, the length of soft scaffold of the robot is about 65mm, and the overall size of the robot is 100mm ×6mm×20mm. In the state of inflation, the soft scaffold deploys into a hexagonal prism with a length of 55mm, and the bottom side length of the prism is 30mm. The tip workspace of the robot can reach 40mm in all three directions of the local coordinate system.

## MATERIALS AND METHODS

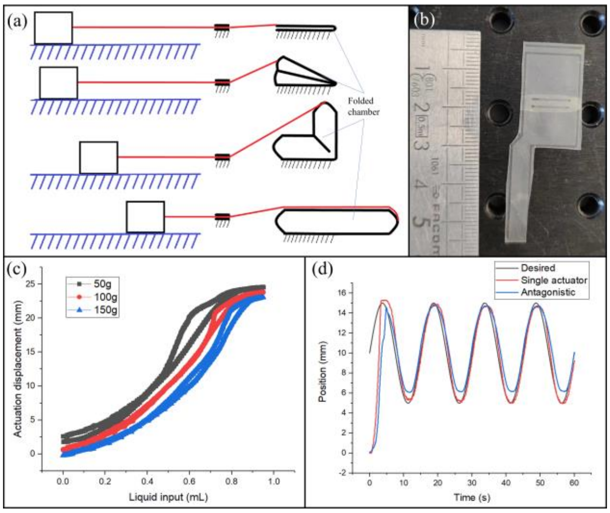


**Fig. 1** Test of the hydraulic folded actuator. (a) Working principle of the folded actuator. (b) An actuator manufactured by laser welding. (c) Relationship between liquid input in the actuator and actuation displacement under different payloads. (d) Single actuator control and antagonistic control results.

Figure 1(a) shows the working principle of the actuator. Initially shown is a folded chamber with no liquid or gas in it. One end of the chamber is connected to a cable through a small hole, which then connects to a slider. When the chamber is inflated, the folded chamber will deploy and pull the slider to move. When the chamber is fully deployed, the displacement of the slider is nearly equal to the length of the chamber. Figure 1(b) shows a fabricated actuator, which is made of plastic film laser welded as shown in [3]. The length of the inflatable part of the actuator is 25mm and the width is 15mm. Due to the incompressibility of liquid, a hydraulic actuator can be open-loop controlled. Here we use water as hydraulic media. The cable is connected to a slider with a retroreflective marker. The cable displacement is measured by tracking the position of the marker. Figure 1(c) shows the relationship between the cable displacement and the liquid input in the actuator. To make the cable reciprocate, weights are hung on the cable via a pulley. The displacement of the actuator almost reaches the length of the chamber. When the actuator is in a large displacement, the hysteresis decreases as the payload increases. This is because when the payload is small, the chamber has a certain stiffness. Even if it is not completely filled with liquid, it still has some stiffness and is not easily folded. The mathematical expression of the plot is obtained by curve fitting, which can be used for position control of the actuator. Figure 1(d) shows the position tracking results of a single actuator and of a pair of actuators in antagonistic mode. When the payload is 100g, the tracking accuracy for single actuator is high. In this case, the accuracy may decrease if the payload is unknown. In the antagonistic mode, the cable tension between two actuators is unknown, so tracking accuracy decreases.

## RESULTS

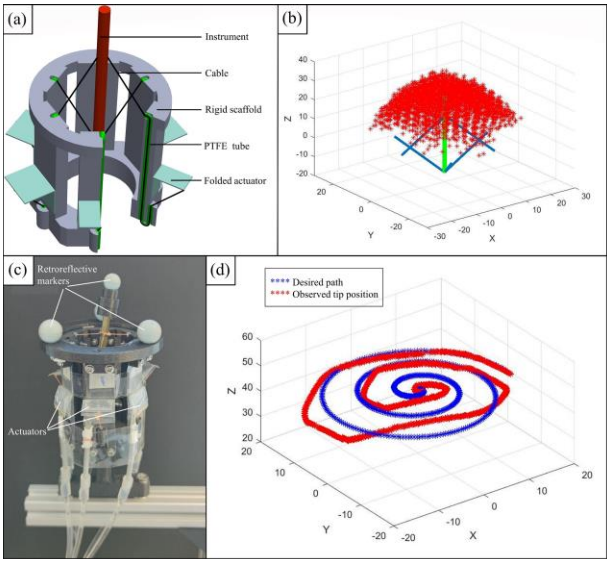


**Fig. 2** 6-cable parallel robot test. (a) 3-D model of the robot (actuators mounted outside). (b) Workspace of the robot. (c) Path scanning experiment setup. (d) Result of path scanning experiment.

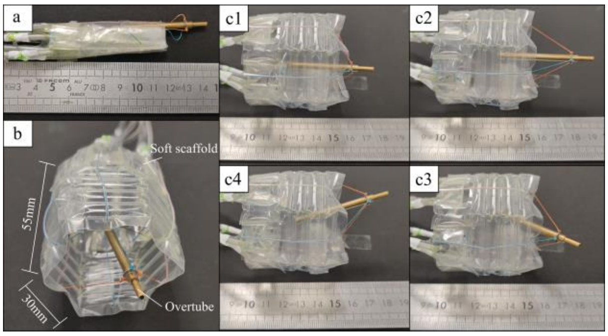


**Fig. 3** Deployment and use of the pop-up robot. (a) Robot in folded state. (b) Front view of the deployed robot (actuators mounted inside). (c1-c4) Side view of the deployed robot. The overtube has different poses.

Figure 2(a) shows a parallel robot driven by 6 cables, including a rigid scaffold, six proposed actuators and a cylindrical instrument. The cables are connected to the instrument through PTFE tubes in the rigid scaffold. Figure 2(b) shows the workspace of the robot, in which the cable displacement limit is considered. Figure 2(c) shows the test setup. Three retroreflective markers are fixed on the scaffold and one marker is fixed at the tip of instrument. Positions of the markers are tracked by an optical motion tracking system. Figure 2(d) shows the result of scanning a spiral path. The tracking shape is hexagonal due to the friction between cable and channel.

A robot with a soft inflatable scaffold was also built. The folded actuators were welded on the soft scaffold which was previously developed in [3]. The actuators fold towards the interior of the soft scaffold. This robot version is a monolithic device as the scaffold and actuators are included in a single piece. Figures 3(a) and (b) show the folded and unfolded states of the robot. In the folded state, the deflated robot is folded and rolled around the instrument. Figures 3(c1-c4) show different poses of the actuated instrument.

## DISCUSSION

The proposed robot can realize 5-DOF motion of the Cyclops robot in [3]. This means that the pitch and yaw angle of the instrument can be adjusted when its tip is fixed on a certain position. In the soft robot system, 6 folded hydraulic actuators are mounted in a confined space, but they do not collide with each other when working as the actuators are small enough. Being a cable-driven parallel robot, antagonistic actuation is required, which somewhat reduces the achieved open-loop tracking precision. This is due to cable friction and variable cable tension. The second reason may be that the two folded parts of the chamber do not perform the ideal movement when folding and unfolding as shown in figure 1(a). For example, the crease sometimes does not appear in the desired position. In future work, in-built sensors can be applied to help measure or estimate the cable tension to improve the actuator and robot control accuracy.

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