Pop-up Soft Robot for Minimally Invasive Surgery

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June 1, 2022

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INTRODUCTION

Colorectal cancer was estimated to have caused the second highest number of cancer-related deaths globally in 2020, and the third highest number of incidences [1]. As a result, there is an intense research focus on developing improved screening and treatment options. Among recently developed surgical techniques for early colorectal cancers is Endoscopic Submucosal Dissection (ESD), which offers patient benefits such as reduced recurrence rate, the possibility of removing large early cancers *en bloc*, and increased resection rate [2], in comparison to the more common procedure Endoscopic Mucosal Resection (EMR). However, procedure times and perforation rates are higher for ESD as a result of the high technical difficulty [3].

Robotic devices may simplify difficult ESD procedures, lessening the learning curve and/or reducing the staff required; however, there is no standard flexible robotic endoscope in spite of recent advances. Challenges facing designers of robotic devices include reducing patient discomfort and achieving cecal intubation rates comparable to standard endoscopy [4]. Cecal intubation is achieved when the endoscopist successfully reaches the cecum with the endoscope, and bulky robotic mechanisms can make navigation and insertion harder and cause increased patient discomfort, resulting in the need for sedation or longer procedure times.

Here we present an inflatable robot capable of volume, size, and stiffness changes as an answer to the need for surgical robots that can achieve access to the proximal colon. To the authors' knowledge it is the first robot for minimally invasive surgery whose structure and actuators were made using laser welding manufacture, and the design is low-profile and low-cost as a result. This work builds on the inflatable Cyclops robot [5] but replaces the long force transmission cables with soft hydraulic actuators as described in [6]. As such, both the robot's structure and actuators are made from flexible plastic film. One of the main benefits of this construction is that the robot can easily be collapsed to a small size by folding and/or rolling, then deployed by pressurising the structure. The robot therefore has two states: an inactive, deflated, flexible state, and an active, pressurised, rigid state. The folded state can be approximated by a cuboid of 25 x 7.5 x 100 mm and the deployed state by a cylinder of approximately 44 mm in diameter and 100 mm in length. The tip position of a single 3 mm diameter flexible instrument can be controlled by the robot while in its active state. The ranges of motion in the local coordinates of the robot are approximately 47.0 mm, 92.5 mm, and 89.0 mm in the X, Y, and Z directions, respectively. The X axis is positive along the shaft, the Y axis horizontal and the Z axis vertical.

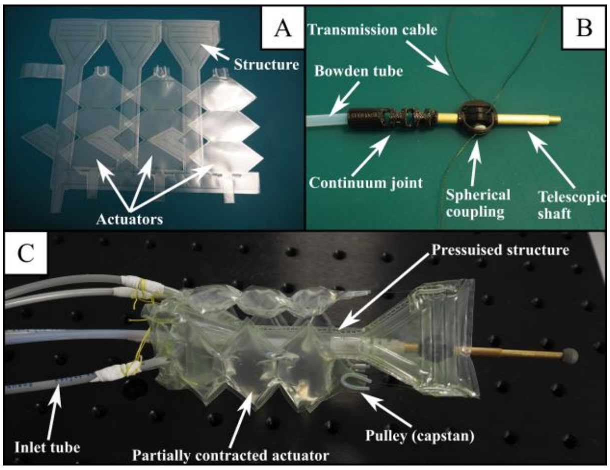

Fig. 1 Inflatable robotic device A) Laser-welded actuators affixed to laser-welded structure during construction. B) Shaft assembly with PTFE Bowden tube, 3D printed continuum joint, telescopic shaft, and spherical coupling connecting the transmission cables to the shaft. C) Complete robot with pneumatically pressurised structure and hydraulic actuators.

MATERIALS AND METHODS

A hybrid parallel mechanism was chosen as a trade-off between the number of actuators and the degrees of freedom, resulting in a polar robot whose tip can be positioned with 3 degrees of freedom. The robot is composed of a shaft assembly, inflatable structure, and soft actuators. The structure and actuators, shown in Figure 1A, were manufactured using laser welding of thin plastic films, described in [5], to create sealed chambers. The structure and actuators were welded separately, the excess material removed from each, then the actuators manually welded to the structure at specific anchor points. The shaft assembly, Figure 1B, consists of a 3D printed passive continuum joint, a telescopic brass shaft, and a 3D printed spherical coupling to attach the three transmission cables to the shaft. Except for the shaft assembly, all parts of the robot are capable of reversible changes in volume, shape, and rigidity. The proximal end of the continuum joint couples to the inflatable structure to provide a lever point. The parallel mechanism controls the point through which the shaft intersects the plane made by the locations where the cables enter the inflatable structure. In this way the pitch and yaw of the shaft are determined. The length of the telescopic shaft is changed by actuating a flexible tube through a Bowden tube connected at the base of the continuum joint.

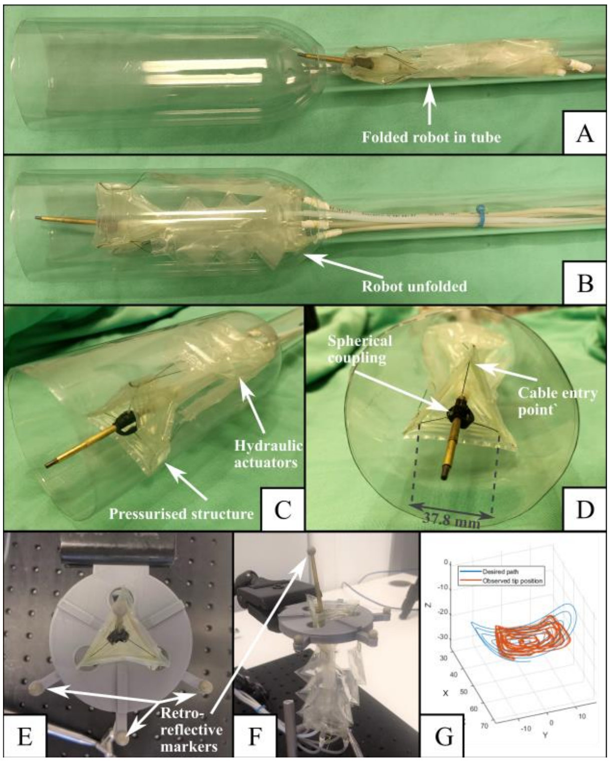

Fig. 2 Deployment and use of deformable robot. A) Passing through insertion tube B) Unfolding at target C) Pressurised robot ready to use D) Close-up showing cable entry points, spherical coupling, and telescopic shaft E&F) Path scanning experiment setup G) Result of path scanning experiment – ten repetitions of spiral path projected on cylinder.

The contraction of the soft hydraulic actuators is determined by controlling their volume, as discussed in [6], which was achieved in this work using individual syringe pumps. A block and tackle pulley arrangement was used between the structure and each actuator to double the stroke, thereby reducing the required actuator length by a factor of two.

An optical tracking system (Optitrack, NaturalPoint Inc.) was used to observe the position of the tip during a path scanning task. A retroreflective marker was placed on the tip of the robot, with others in a reference pattern defining the cable entry plane and the centre of the planar parallel mechanism. The setup is shown in Figures 2 E and F.

RESULTS

Figure 2A-D shows the robot was able to deform before its deployment and subsequent use. In Figure 2A the deflated robot was folded and rolled around the shaft assembly, then passed through an insertion tube to a larger void, Figure 2B. For deployment, Figure 2C, the inflatable structure was pressurised to 2 bar absolute using a pneumatic regulator (PRE1-U08, AirCom, Germany). Pressurising the structure caused it to unfold, increase its size and rigidity, and correctly position the cable entry points of the integrated parallel mechanism relative to each other. As such, the robot was able to scan complex paths. Figure 2G shows the result of scanning a spiral pattern projected onto a cylinder aligned with the robot's central axis.

DISCUSSION

The robot was made from low-cost materials using rapid manufacturing techniques, creating the possibility for single-use and even patient-specific robotic devices for minimally invasive surgery. Additional automated manufacturing steps such as laser cutting could further reduce assembly times and increase scalability. Benefits of this approach in a fully developed system could include infection control and reduction in operational costs that could make robotic surgery more accessible. The ongoing aim of this project is to create pop-up soft robotic devices capable of accurate and precise path scanning for diagnostic and therapeutic uses.

The inflatable robot was able to pass through an insertion tube, pop up by inflating its support structure, and scan a complex path. The path scanning was more inaccurate than anticipated due to bending of the structure, however, in another tracing task, a human user manually compensated for the robot's motion in real time to successfully trace a circle. Therefore, the authors expect that inaccuracies may be compensated for in future versions of the device with a stiffer structure and by using visual servoing, for example. Other innovations for future versions could involve replacement of the brass shafts with plastic shafts to make the device MRI compatible. The length of the robot could be greatly reduced, for example, by changing the design of the pulley mechanism.

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