Miniaturisation, Modularization and Evaluation of the SoftSCREEN System

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INTRODUCTION

Early detection of precancerous forms in the intestine, e.g. adenomatous polyps, can be achieved with regular screening programmes of the lower gastro-intestinal tract (GI) by means of flexible sigmoidoscopy and colonoscopy. Screening of the GI tract is of paramount importance to reduce the high death rate of patients affected by colon cancer worldwide. Nonetheless, colonoscopy typically causes discomfort and often requires sedation for the patient because of its invasiveness and abdominal pain associated with it. Research on robotic-assisted colonoscopy is advancing in the design of minimally invasive devices aimed at the inspection of the GI, with the goal of reducing the discomfort caused to the patient while resulting in a safer and more successful procedure [1]. Multiple locomotion strategies have been explored to enable front-head locomotion of endoscopes, to minimise the interaction forces between the scope and the intestine wall, as these forces are typically the first cause of discomfort for the patient. Extensive studies have been conducted in the context of track-based miniaturised robots such as [2] and [3]. However, due to the fixed geometry of these systems, adapting to the variable and irregular lumen of the colon to enable full body track-based navigation is not possible. Furthermore, as per many of the robotic solution presented to date for GI screening, there is also a need to drag a tether, the frictional resistance of which grows the more the robot advances in the intestine. Soft materials properties have inspired research of mechanism to accomplish a compliant interaction with the tissue, such as the use of inflatable balloons for double balloon endoscopy. In our previous work [4], we have presented a novel robotic system for colonoscopy called SoftSCREEN. The proposed system relies on track-based locomotion and shape reconfiguration enabled by two inflatable chambers capable of displacing the elastic tracks to conform to the local geometry of the lumen, enabling full-body track navigation. In this seminal paper we have validated the proposed desing in a 2:1 scale system and demonstrated that not only is possible to reconfigure our system to always match the lumen navigated, but also to control the force applied on the walls by means of pressure regulation, and, as a result, fine tuning the traction force of our system. In this work, we present the first miniaturised and modularised prototype of the SoftSCREEN system, designed to create a sterilisable reusable expensive component and a cheap disposable component. We then evaluate this first prototype in a 1:1 scale phantom.

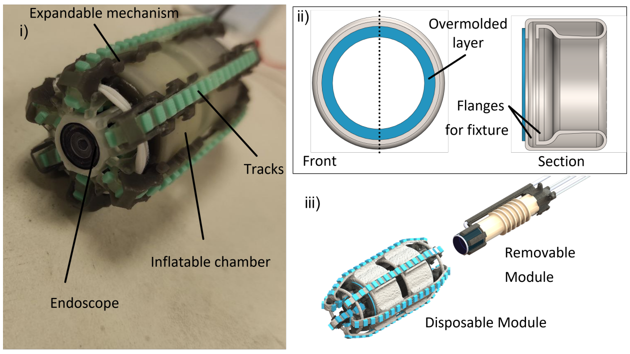

Fig. 1: Overview of the SoftSCREEN system. Picture of the robot mounting a front endoscope (i). Design of the of the inflatable chambers with reinforced-flange obtained by overmolding hard silicone (in blue) on the inflatable membrane (ii). Assembly of the robot by the insertion of a removable/resuable module into a disposable module (iii).

MATERIALS AND METHODS

The design presented in this work builds on the one firstly proposed by the authors in [4]. Here we are presenting a small-scale version (30 mm in diameter) of this system. As in our previous design the system is composed of a rigid chassis, a motor-powered worm-gear mechanism, six elastic tracks and two inflatable toroidal chambers, as shown in Fig 1-i). The robot mounts a 0.5 W DC Motor with gearhead (both from Maxon Motor™, Sashseln, Switzerland) and a full-HD endoscope (Misumi Electronics Corp., Taiwan) front facing and with integrated illumination. The rotation of the motor cause the rotation of the worm gear which displace all the elastic tracks that move in loop around the chassis and generating the linear movement of the robot by engaging with walls. Direction of motion of the robot depends on the direction of rotation of the motor. Inflation of the toroidal chambers is used to displace and deform the tracks to ensure contact with the lumen, thus traction. To enable shape reconfigurability flanges were embedded on the external surface of the chassis on the distal ends to facilitate chambers installation, sealing, maximise radial expansion and minimise the axial one. Flexibility of the distal ends of the track guides on the rigid chassis was also achieved by means of an expandable mechanism comprising multiple segments connected by hinges, as discussed in [4]. In the design presented here we have optimised this expandable mechanism, creating a chain of three links that provides laterally constraints the movement of the tracks while conforming to the system's inflated shape. In our design, we connect soft chambers subjected to high deformation to a rigid structure using screws

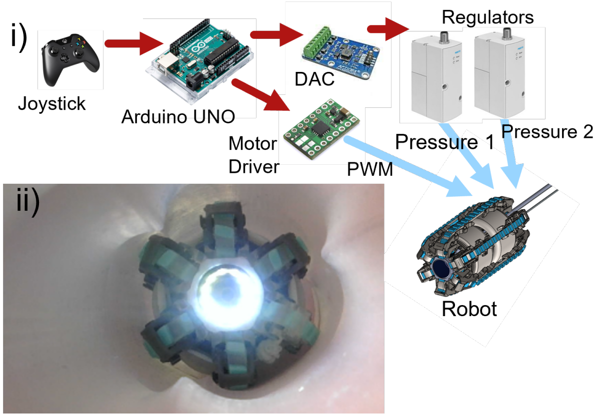

Fig. 2: Control scheme of the robot for the experimental setup. The user controls the robot using a joystick controller. The Arduino board controls the DC motor driver and the two pressure regulators to enable track motion and independent inflation of the chambers (i). Picture of the SoftSCREEN inside the phantom (ii).

passing through it. Both from simulation and from experiments this connection was found to be the point of higher stress concentration in the chambers that could lead to failure. To reinforce the membrane at the position of the screws, multi-material inflatable chambers were created by overmolding a layer of hard silicone on the flanges of the soft membrane, as shown in Fig 1-ii), to guarantee both high deformation and a robust fixture. Envisioning the robot being used in a clinical settings, we decided to modularise our system creating two modules depicted in Fig 1-iii: the first module is disposable being composed of a plastic chassis and silicone-based inflatable chambers; the second module is reusable after sterilization, and this embeds all the expensive components, namely the motor, the worm-gear and the optics. In the deflated state, the prototype is 32 mm in diameter and 60 mm long. The rigid parts are made of photopolymer resin, printed with a 3D-printer (Formlabs™, Somerville, MA, US). The toroidal chambers are 0.60 mm thickness membranes made of Dragon Skin™ 10 NV silicone rubber (Smooth-On Inc., Easton, PA, US), flange-reinforcement and tracks are made of Smooth-Sil 960™ from the same brand. The tracks are composed by two silicones combined together with overmolding, Dragon Skin™ 30 for the body of the track and Smooth-Sil™ 960 for the teeth. The users can control speed and pressure of the two chambers by using a joystick as shown in Fig 2-i). The two chambers are actuated pneumatically via pressure regulators (VPPX-6F-L-1-F-0L10H-S1, FESTO GmbH, Esslingen, Germany), where the pressure is controlled via a Arduino UNO microcontroller connected to a DAC (DA4C010BI, APTINEX Ltd., Maharagama, Sri Lanka). The motor is driven by a DC (DRV8876, Pololu, Las Vegas, NV, US). An experimental setup was assembled to assess the shape-shifting capability of the flange-reinforced actuators. The diametrical expansion of the robot was monitored by image analysis through a camera (C922, Logitech, Switzerland). The locomotion of the robot was then tested inside a straight segment of tubular phantom made of EcoFlex™ 30, 25 cm long with circa 30 mm in diameter (Fig 2-ii).

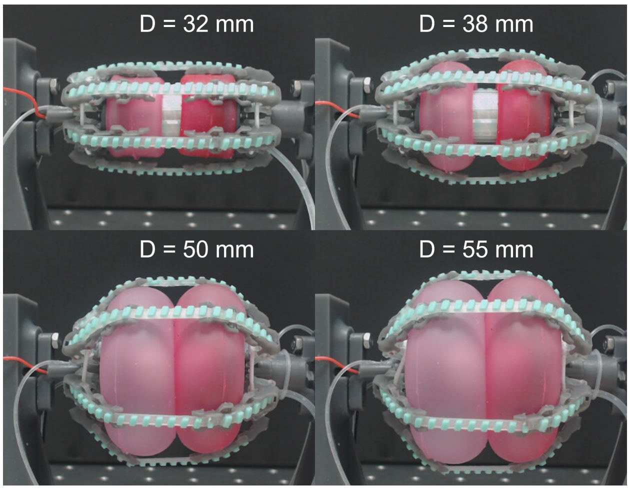

Fig. 3: Pictures of the experimental setup for the robot to assess the capability of reconfigure its shape. The soft chambers (red membranes) are inflated at 4 different levels of pressure, with the robot fixed on a rigid stand. The overall maximum diameter of the robot is displayed in the figure. The inflation of the chambers displaces the tracks (clear green) outward while the expandable mechanism sits below the tracks and above the chambers.

RESULTS

A selection of images captured during the data acquisition for are presented in Fig. 3, showing the deformation of the system at different pressure levels. The robot was assembled as described and fixed to a rigid structure to assess the inflation in a static condition. The overall enlargement of the robot was measured from the initial diameter of 32 mm to circa 55 mm, meaning that the design of the inflatable chambers as proposed allows the robot to almost double its diameter. Inside the phantom, the robot moved forward and backward as fast as 3 mm/s and provided clear image recording of the lumen.

CONCLUSIONS AND DISCUSSION

In this work We presented the first miniaturised version of the SoftSCREEN system for colonoscopy, demonstrating track locomotion and reconfiguration capabilities, and optimising the design for modularisation. In the experimental setup, the robot has demonstrated to be able to expand its diameter in a wide range and to move inside a straight silicone phantom. In future, a closed-loop control strategy will be considered to match the robot diameter to that of the lumen, and the locomotion of the robot will be extensively tested in more complex phantom settings.

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