SoftSCREEN – Soft Shape-shifting Capsule Robot for Endoscopy based on Eversion Navigation

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INTRODUCTION

Colorectal cancer (CRC) is the third most commonly diagnosed malignancy and the second most common cause of cancer-related deaths worldwide [1]. Conventional colonoscopy represents the gold standard for the evaluation of diseases of the colon and for CRC diagnosis [2]. However, this screening procedure is considered invasive and discomfort, pain and potential tissue damage can occur for patients. Ingestible endoscopic capsules have been developed to overcome the drawbacks of the standard colonoscopy. Despite the advantages offered by these wireless devices, their main limitation is that their motion depends on natural bowel peristalsis only and it is not possible to control capsule motion and camera orientation [3]. Magnetic capsules instead rely on external magnetic fields to overcome the lack of controllability of standard ingestible capsules, however, they require bulky and expensive equipment to be actuated with enough precision and force [4].

To actively and reliably control the movements of an endoscopic capsule system a number of embedded locomotion approaches have been explored, with a robotic solution integrating cameras, biopsy tools, water channels for lens cleaning as well as an air canal colon local inflation to enhance visibility of the inspected area being proposed by multiple research groups [4].

Systems based on rigid mechanical elements, like the robots presented in [5], [6], can cause damage to the soft walls of the navigated GI tract despite their active motion capabilities. For this reason motion techniques based on treaded tracks [7] and elastic caterpillars [8] have been suggested. In [7], the rigid endoscopic capsule has four soft tracks powered by a worm-gear transmission and has successfully demonstrated benefits in terms of navigation speed, however, due to the fixed geometry of the proposed system, the four tracks are never simultaneously in contact with the walls, significantly reducing the controllability of the system. The robotic endoscopic system shown in [8] instead makes use of elastic tracks that passively deform to match the local lumen of the colon. This arrangement ensures a central positioning of the capsule body, however, its motion is strongly affected by the gravity action as well as by the lack of direct control on the geometry of the system, hence, of the interaction forces between the tracks and the wall of the GI tract.

In this paper the Soft Shape-shifting Capsule Robot for Endoscopy based on Eversion Navigation (SoftSCREEN) is presented for the first time – a novel capsule-sized system that propels itself through the GI tract by means of a series of continuously everting elastic tracks distributed all around its body. A proof-of-concept 2:1 scaled prototype is proposed as shown in Fig. 1. The system consists of a rigid cylindrical body (Fig. 1-b, light blue) which encases a worm gear powered by a motor.

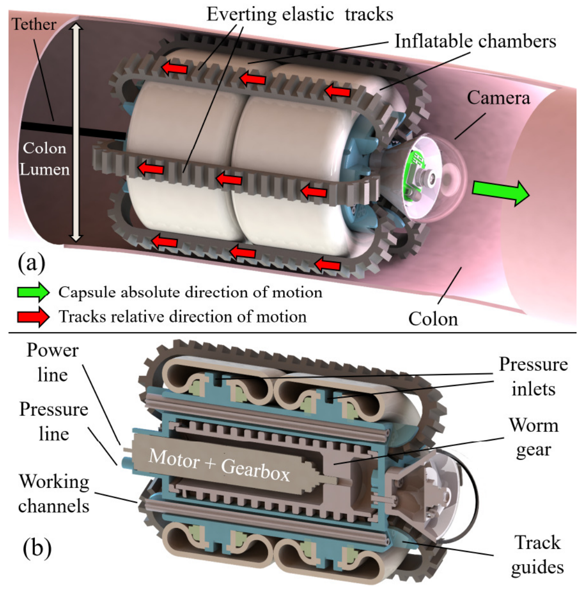

Figure 1 – (a) SoftSCREEN System motion principle: the inflation of the chambers ensures the contact of the tracks onto the colon walls. (b) Section of the 2:1 scaled prototype.

The motion is provided by six elastic tracks engaging with the worm gear teeth, regularly distributed around the capsule lateral surface. Differently from other track-based capsule designs, the geometry of the SoftSCREEN system can be changed by pressurising the two toroidal chambers displayed in white in Fig. 1. When the chambers are inflated, the elastic tracks are deformed in the part not engaged in the worm gear. This design feature allows to match the local lumen of the GI tract, ensuring constant traction of all the tracks. The proposed inflatable mechanism allows also for self-alignment of the system with the central axis of the targeted section, thus providing a stable and consistent position for the camera embedded for navigation and screening. The revolution of the worm gear leads to the revolution of the tracks around the inflatable chambers and along the length of the capsule, enabling navigation (Fig. 1-a). The colon lumen diameter varies in a range between 30 to 90 mm; therefore, the scaled prototype has 60 mm diameter at rest and it enlarges up to 180 mm diameter. The proposed design embeds a camera and the space for air and water channels.

MATERIALS AND METHODS

The CAD model of the prototype is shown in Fig. 1-b. A rigid chassis encloses a 10 mm diameter brushless DC motor (Maxon 315170 motor, 332426 gearbox) paired with a worm gear, both arranged longitudinally. The elastic tracks (Fig. 2-a) are made of Dragon Skin™ 20 silicone (Smooth-On Inc., Easton, PA, US), have a planar

This work was supported by the Wellcome/EPSRC Centre for Interventional and Surgical Sciences (WEISS) at UCL (203145Z/16/Z), EPSRC (EP/P027938/1, EP/R004080/1). Danail Stoyanov is supported by a Royal Academy of Engineering Chair in Emerging Technologies (CiET1819_2_36) and an EPSRC Early Career Research Fellowship (EP/P012841/1). Agostino Stilli is supported by a Rosetrees Trust/Stoneygate Trust Enterprise Fellowship (M884).

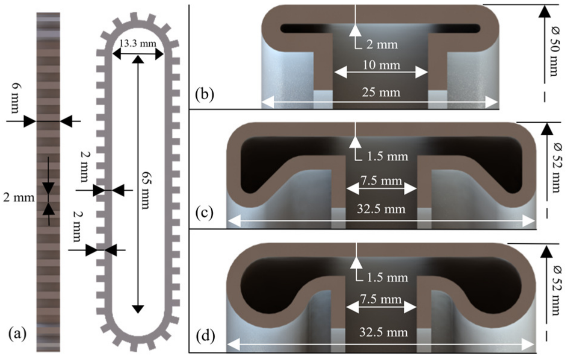

Figure 2 – (a) track dimensions, (b) simple chamber profile. (c) squared chamber profile and (d) rounded chamber profile.

low-friction internal surface to slide on the chambers and a series of teeth on the external surface to engage with the worm gear inside the chassis, while providing the desired friction when interacting with the walls of the colon. As the tracks, the chambers are made of Dragon Skin™ 20. As shown in Fig. 1-b, the chambers are secured to the chassis by means of flanges embedded in the chassis, custom rings (in green) and screws, creating an air-tight connection. Air in pressure is supplied to the chambers the circumferential pressure inlets shown in Fig. 1-b: these are connected to the pressure supply through a 1 mm diameter longitudinal pipe built into the chassis. Additionally, space for six 2 mm diameter channels is available for pressure lines, tendons or electrical cables.

In this paper we present a preliminary design study focusing on Finite Element Method (FEM) static analysis of the chambers and of the tracks, using Dragon Skin™ 20 silicone as material – the mechanical parameters of which have been obtained from [9]. The aim of this study is to optimize the design of the chambers to achieve the desired radial expansion (180 mm), without exceeding the diameter at rest of 60 mm. In Fig. 2-b/c/d we present three designs: in (b) we minimise the radial encumbrance at rest, in (c) we maximise the section area and in (d) we maximise the internal curvature. These profiles have the following geometrical features (expressed as middle line perimeter of the section profile, deformable silicone volume, thickness):(b) 39.42 mm, 11.83 cm³, 2 mm; (c) 66.39 mm, 13.94 cm³, 1.5 mm; (d) 68.9 mm, 14.77 cm³, 1.5 mm. A larger section area ensures more material to deform, while a large and uniform curvature prevents localised areas of high stress, that could lead to rupture of the chamber. Profile (c) has a longer section perimeter and internal curvature radius of 1 mm/1.5 mm. Profile (d) has shorter section perimeter but features a uniform internal curvature radius of 3 mm. Finally, with respect to profile (b), both (c) and (d) are as wide as the chassis and have closer flanges to further increase the amount of deformable material, with slightly decreased thickness.

RESULTS

Due to computational limitations of the FEM software used (Ansys 19.0, ANSYS Inc.,US) the proposed profiles were tested deforming them only up to a third of their desired deformation in two scenarios: single chamber free inflation (3D study) and chambers-track interaction (2D study), modelling also the track (Dragon Skin™ 20) and the chassis (steel). The results of the simulations are illustrated in the Fig. 3. Fig.3-a shows the circular profile on the left as the best for the free inflation, with a maximum stress of 0.675 MPa, while the right profile exhibited maximum stress 0.758 MPa, with a radial deformation of 21 mm in both cases. In the chambers-track interaction case (Fig. 3-b) instead, the squared profile showed less localized maximum stress, peaking at 0.326 MPa, while the circular one peaked at 0.369 MPa, in both cases for a radial deformation of 20.3 mm.

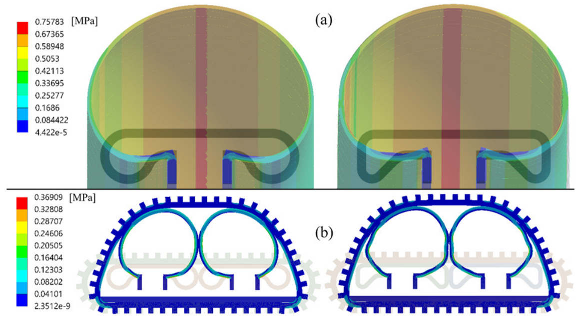

Figure 3 – (a) 2D track/chamber simulation for circular (left) and squared profile (right). (b) 3D free inflation for circular (left) and squared profile (right).

CONCLUSION AND DISCUSSION

In this work, a novel design for an endoscopic shape-shifting robotic capsule is presented. A proof-of-concept system is presented, investigating a 2:1 tethered version, focusing on colonoscopy. The large deformation of the inflatable and elastic elements composing the envisioned variable geometry mechanism pose the biggest design challenge. A preliminary FEM analysis of different designs for the inflatable chambers showed that a large and continuous curvature radius results in lower maximum stress in the free inflation scenario, while the larger amount of material in the squared profile results in a lower stress in the chamber-track interaction scenario. Regardless of the geometry, in both cases the maximum stress measured for a third of the desired deformation is ten times smaller than the tensile stress of the silicone rubber tested (3.8 MPa). These results will be validated in real prototypes in the sooner future.

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