RollerBall: a mobile robot for intraluminal locomotion*

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Abstract— **There are currently a number of major drawbacks to using a colonoscope that limit its efficacy. One solution to this may be to use a warm liquid to distend the colon during inspection. Another is to replace the colonoscope with a small mobile robot – a solution many believe is the future of gastrointestinal intervention. This paper presents RollerBall, an intraluminal robot that uses wheeled-locomotion to traverse the length of a fluid-filled colon. The device provides a central, stable platform within the lumen for the use of diagnostic and therapeutic tools. The concept is described in detail and the feasibility demonstrated in a series of tests in a synthetic colon.**

I. Introduction

Colonoscopy is currently the gold standard for diagnosis and treatment of a range of colorectal diseases, including colorectal cancer [1]. Early diagnosis can greatly improve cancer survival rates [2], so the reliability of the procedure is of utmost importance. Despite its frequent use, there are a number of drawbacks to using a colonoscope (endoscope), namely: impaired visibility due to poor bowel preparation; patient discomfort from looping of the colonoscope; and limited access caused by bowel tortuosity [1, 3].

A potential solution is to use a mobile endoscopy robot instead of the traditional colonoscope. The high mobility and small scale of such a robot could allow more reliable access to the GI tract, as well as improved vision and reduced patient discomfort. On-board surgical tools could also be used to carry out localized treatment [4]. Another modification could be the use of a warm liquid to distend the colon during inspection (hydro-colonoscopy). This has been shown to globally distend the colon for MR imaging [5] and to reduce patient discomfort by decreasing colonic spasm [6]. The global distension is likely to favorably change the properties of the colon, giving it a firmer, more defined structure. This would facilitate access to difficult regions as well as improve visibility of the mucosa for diagnosis.

Using a mobile endoscopy robot in a fluid filled colon could be an optimum solution and one that, to the authors' knowledge, has not been thoroughly explored. The primary requirements for the robot are as follows:

- Be small enough to allow easy traversal of narrow apertures and acute bends without applying excessive pressure on the surrounding tissue.
- Provide a stable platform[1] in all regions of the distended colon to allow diagnostic and therapeutic tools to be used effectively.
- Have a locomotion mechanism that allows it to move effectively through the tortuous, distended colon.

The locomotion technique used is key to the success of such a device. To date, most intraluminal (upper and lower GI tract) robots have used one of three classes of locomotion.

Inchworm technique: This involves a long slender robot that sequentially anchors and extends parts of its body. Although this has the advantage of a small diameter, it is associated with low efficiencies and slow movement speeds [7]. It also requires contact with the surrounding lumen to anchor itself during locomotion, yet all devices thus far have not had a diameter that can be varied. This means the device is unlikely to be effective in a distended colon. Furthermore, the absence of a stable platform in the center of the lumen restricts the use of surgical tools (particularly in large diameter sections of the intestine).

Legs or paddles: These approaches rely on the appendages locally, and often excessively, deforming the surrounding tissue to gain traction and propel the device forwards [8, 9]. An obvious limitation is the risk of perforation of the thin colon wall. Additionally, a complex mechanism would be required to actuate the legs in both small and large intestinal apertures.

Magnetic Propulsion: It is possible to manipulate an *in vivo* capsule with an external magnetic field [10]. This has the significant advantage of reducing the device's complexity and size, as an on-board locomotion mechanism is not required. However, stability is dependent on precise control of a high-strength magnetic field, technically challenging and potentially limiting clinical use (e.g. for patients with pacemakers).

With current devices having limited success, there remains a need to find novel solutions. This paper describes RollerBall, a wheeled endoscopy robot that has been designed to satisfy the aforementioned requirements in the context of a hydro-colonoscopy environment. While designed specifically for use in a flooded environment, the authors anticipate that this design could be used in a collapsed colon, air-insufflated colon or for other applications that require intraluminal access.

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[1] Stable platform in this context refers to a fixed, advantageously positioned base within the flexible and mobile colon.

II. System design

A. Overview

The design concept of *RollerBall* (Fig. 1) consists of a compact central body with three radially distributed, extendable arms actuated by an Expansion mechanism. This allows the robot to actively adapt to the size and shape of the environment. Each arm has a spherical drive wheel at the distal end (Wheel mechanism). Wheeled locomotion was chosen because it is simple to realize and actuate at small scales, and provides the potential for continuous control of position. Furthermore, commercially available DC motors can provide high rotational speed and ample torque in a compact package. The spherical shape of the wheels provides high wheel-tissue contact compared to conventional, cylindrical wheels. This is likely to reduce contact pressure (and hence trauma) and increase traction. A tether is used for power and signal communication, and to provide a means of manually removing the device in an emergency. This failsafe is advantageous as it minimizes the need for surgical removal in the event of a device malfunction. The clinician can manually retrieve the robot in its passive state by activating a mechanical release mechanism to collapse the arms and then by pulling on the tether[2]. Surgical tools could be positioned at various locations on the chassis, but our current solution involves a detachable module at the front of the robot[3]. For example, this module could house a camera, light source and embedded control boards (Fig. 1. i.).

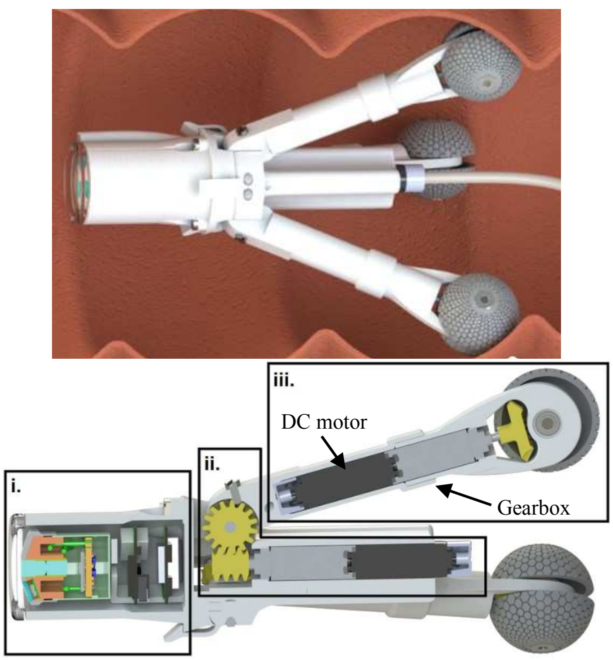

Figure 1. A Render of *RollerBall* in a colon model and a cross-section showing the internal components; i. Electronics module, ii. Expansion mechanism, iii. Wheel mechanism.

The colon is a challenging environment for a robot in part because many of the parameters (including dimensions, morphology, tissue properties and mucosal friction characteristics) are highly variable. It is therefore difficult to define exact specifications for all aspects of the design. The specifications (Table I) are based on the most appropriate data the authors could obtain.

TABLE I. Device Specifications

Requirement	Specification
Small size*	Diameter of 26 mm or less [11].
	Length of 40 mm or less [12].
Stable platform (Expansion mechanism)	Adapt to diameters ranging from ca. 26 mm to ca. 44 – 62 mm [11, 13].
	Provide a normal force of ca. 0.66 N per arm for traction.**
Effective locomotion (Wheel mechanism)	Traverse acute bends.
	Provide a net tractive effort of 1 N or more [8].
	Average linear speed of ca. 3.85 mm/s or more (a wheel rotation of at least 4.5 rpm assuming no slip).***

*With the size and shape of the colon varying considerably between patients, these values are best estimates based on the anatomy and available literature.

** This was calculated assuming the following: Friction is the product of surface roughness and normal force, a conservative friction coefficient of 0.5 (median of average values found in [14]) and a required tractive effort of 0.33 N per wheel (1 N net tractive effort).

*** This was calculated assuming an average colonoscopy takes 8 min to reach the caecum [12] and the colon is 185 cm long [11].

The following sections describe the design of RollerBall in more detail.

B. Expansion mechanism

The expansion mechanism (Fig. 1. ii.) is used to adjust the angle of the three arms and hence the diameter of the device. This has two purposes: to hold the robot in position by ensuring the arms are always in contact with the lumen and; to apply a force normal to the lumen to provide traction. As the primary goal of this mechanism is to provide stability and traction, torque (to preload the arms on the colon walls) is more important than speed, a 6 mm brushed DC motor with a high 221:1 reduction gearbox (Maxon RE6) was used. The motor is located in the central chassis and a worm gear assembly with a 20:1 reduction translates the shaft rotation into an angular displacement of all three arms simultaneously. The magnitude of the expansion force applied normal to the lumen varies with arm angle according to Equation (1),

$$F_N = \tau . L . \cos(\emptyset) \quad (1)$$

where F_N is the force applied normal to the tissue, τ is the output torque of the worm gear assembly, L is the length of the arm and $\emptyset$ the angle between the arm and the chassis. Consequently, the expansion mechanism is less effective at providing normal force in a completely open ($\emptyset = 90°$) configuration. However, the length of the arms ensures this will not be an issue as a completely open configuration should not be required in the apertures expected in the colon. The angle between the arms and the chassis can be adjusted from 0^o (arms parallel to chassis) to 90^o (arms perpendicular to chassis), allowing the current prototype to operate in diameters ranging from 38 – 138 mm.

[2] This release mechanism has not yet been developed.

[3] The liquid medium means that the buoyancy of this module could be designed to help stabilize the robot by counteracting the offset centre of mass.

C. Wheel mechanism

Differentially driving the three wheels can provide propulsive force and control over global position and orientation of the robot's longitudinal axis relative to the axis of the lumen (hereafter referred to simply as orientation). To achieve a linear speed of 3.85 mm/s, the wheels must have a rotational speed of at least 4.5 rpm (assuming no slip). This is relatively low in the context of DC motors and so again, a high torque motor assembly was used (Maxon RE6 with a 221:1 reduction gearbox). The motor rotates the wheel via a 1:1 bevel gear assembly located inside the wheel itself, resulting in a simple and compact mechanism (Fig. 1. iii.). The success of the locomotion mechanism, and indeed the whole device, is dependent on the wheels gaining sufficient traction. A number of authors have shown that the use of a tread pattern can effectively increase friction against the intestinal surface without causing significant trauma to the tissue [14 – 18]. A simple tread pattern consisting of perpendicular (to the direction of travel) grooves was therefore used for the first prototype.

D. Control

An open-loop control method is currently used (Fig. 2). A graphical user interface was designed using LabVIEW software (National Instruments) and all signal processing is performed by a myRIO controller (National Instruments). The motors are powered (via the tether) by a benchtop power supply and custom-made external motor driver boards. A games console controller (Microsoft, Xbox 360) was chosen to control the robot because of its intuitive layout. The 'x' and 'y' coordinates of the two analogue joysticks are used to adjust movement speed (Left joystick) and orientation (Right joystick) of the device by proportionally altering the speed of the required motor(s) using a simple software algorithm. The two analogue triggers are used in a similar way to expand (Left trigger) or contract (Right trigger) the arms. The absence of sensor feedback means a direct line-of-sight between the user and the robot is currently required[4].

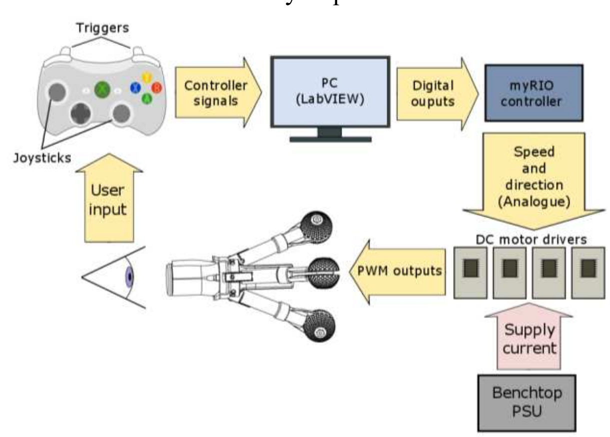

Figure 2. The open-loop communication architecture for RollerBall.

[4] In this paper, experimental work was carried out in transparent silicone tubes, allowing a real-time assessment of wheel contact and robot position.

III. Prototype Fabrication

The prototype (Fig. 3) was fabricated out of an ABS-like material (EnvisionTec, AB10 resin) using a DLP 3D printer (EnvisionTec Perfactory 3 mini, multi-lens). This printer has a resolution between 15 and 60 µm and is suitable to recreate the complex parts with a push-fit tolerance between them. The bevel gears in the wheel mechanisms were also 3D printed, while the worm and spur gears were machined out of steel and brass respectively. Bearings (OD= 5 mm, ID= 2 mm) were used to support the wheel and expansion mechanism axles. No attempt was made to seal the robot as no organic materials or liquids were to be used in the experiments. A dummy electronics module was attached to the prototype to give realistic dimensions and weight distribution as all control hardware is currently externally located. The overall length and diameter of the robot (in a fully collapsed configuration) are 95 mm and 38 mm respectively.

Figure 3. The 3D printed prototype.

IV. Experimental Methods

Benchtop tests were first carried out to assess the performance of the wheel and expansion mechanisms. The maximum angular speed of both mechanisms was measured by recording the time taken to complete a fixed displacement in an unloaded condition (5 revolutions of the wheel and 0 – 90° for the expansion mechanism, n = 5). This was measured visually using a video camera. A custom built traction rig was then used to measure the maximum tractive effort of the wheel mechanism (n = 10). A single wheel from RollerBall was pressed into a block of silicone in such a way as to prevent rotation. The silicone block was connected to a single-axis load cell (Transducer Techniques GSO-150). Current to the motor was progressively increased and the load cell monitored to measure the maximum tractive effort. This configuration was then modified to record the maximum expansion force provided by the expansion mechanism (n= 10). A single arm was supported above the load cell, perpendicular to the loading axis. Current to the expansion mechanism was then increased linearly and the maximum blocked force measured.

Once the performance of the individual mechanisms were characterized, experiments in a synthetic colon were carried out to assess the functionality of the complete Rollerball prototype. Two thin-walled (ca. 1 mm), transparent silicone tubes (Shore A hardness of 40) were fabricated to represent the elastic properties and approximate morphology (varying diameters and multiple corners) of the colon (Fig. 4).

The first tube is straight with a diameter that varies from 90 mm to 40 mm along its length. These values were chosen to represent the varying diameters in the colon [11, 13], but at a slightly larger scale to accommodate the first prototype. It was used to test:

a) The ability to drive forwards in a controllable manner and the speed at which this can be done.

b) The ability to actively control device orientation.

c) The ability to transition from one aperture to another while providing a stable platform.

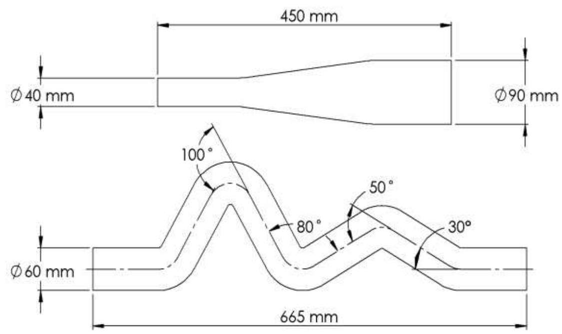

Figure 4. Drawings of the two silicone tubes used for testing.

The second tube is 60 mm in diameter and consists of bends of varying angles. This was used to assess the mobility of the concept and, combined with the benchtop evaluation of the wheel mechanism, evaluate the efficacy of this locomotion technique.

The tubes were suspended by thin nylon threads to allow their free movement and deformation – holding them in an intermediate state between distended and collapsed. Experiments in both tubes were used to assess the intuitiveness of device control. A series of test runs (n = 5) were undertaken to evaluate the performance of Rollerball. In each test:

- RollerBall was placed into one end of the tube.
- The arms were expanded to make contact with the lumen.
- The orientation was adjusted to centrally locate the device within the lumen.
- The user then attempted to drive the robot down the length of the tube using only visual feedback and manual (open-loop) control of position, orientation and arm angle[5].

A single practice run was completed before carrying out the actual test runs. When RollerBall became stuck, the user was allowed a maximum of five maneuvers to free it before stopping the test. The experiments were recorded using a high resolution video camera and qualitatively assessed against the requirements.

V. RESULTS

The performance of the constituent Rollerball mechanisms are summarized in Table II.

[5] The user was familiar with the prototype and had previous experience with using an Xbox controller.

TABLE II. THE BENCHTOP PERFORMANCE OF THE INDIVIDUAL MECHANISMS

Parameter	Required	Benchtop
Wheel velocity	> 4.5 rpm	90 ± 0.84 rpm* (n = 5)
Tractive effort (per wheel)	> 0.33 N	2.98 ± 0.71 N (n = 10)
Expansion velocity	N/A	0.99 ± 0.04 rad/s* (n = 5)
Expansion force (per arm)	> 0.66 N	0.99 ± 0.11 N ** (n = 10)

* Unloaded condition.
** High friction between the arms and the chassis was noted.

RollerBall was successful in traversing the full length of the variable diameter tube in all five repetitions. This indicates that the expansion mechanism is effective in allowing movement through changing apertures (Fig. 5a.). Moreover, the orientation could be rapidly adjusted to maintain a posture central to the lumen (Fig. 5b.). The average speed while manually controlling propulsion, orientation and arm position in this tube was 4.9 ± 1.7 mm/s (n = 5). However, peak linear speeds of ca. 22 mm/s were achieved in the constant-diameter sections of the tube.

RollerBall was successful in traversing the majority of the corners during tests in the bent tube (Fig. 6). The success rate for each corner of the tube is shown in Table III (n = 5).

TABLE III. SUCCESS RATE FOR EACH CORNER

Corner angle	30°	50°	80°	100°
Success rate (%)	100	80	60	60

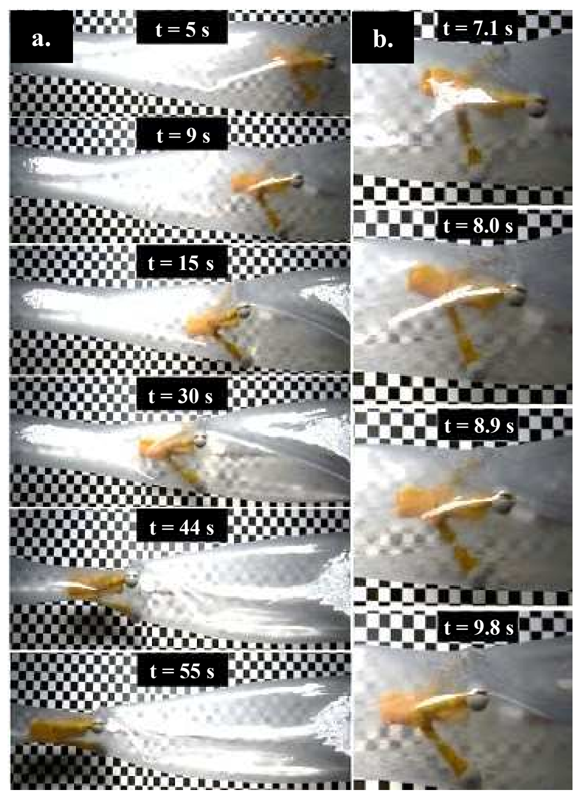

Figure 5. Sequence of images from a single repetition in the first tube with varying diameters; a) one complete run, b) the rapid adjusting of RollerBall's orientation. *(The checkered grid consists of 1 cm squares).*

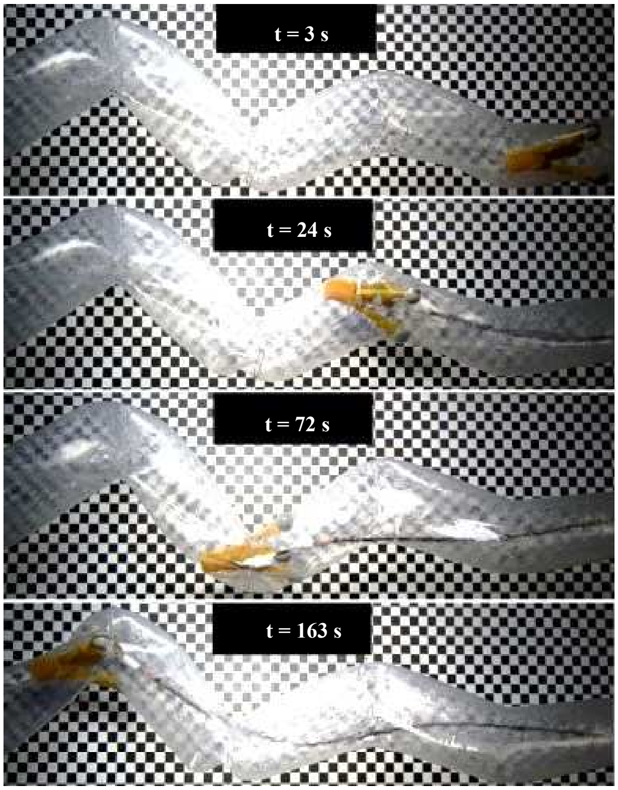

Figure 6. Sequence of images from a single repetition in the tube with multiple corners.

VI. Discussion

The material and fabrication technique used for the prototype were suitable for this feasibility study, and there was no visible damage to the device after more than 5 hours of testing and handling. The scale of the current prototype slightly exceeds the size requirements, primarily because of the size of the DC motors. These 6 mm motors provide excess torque, particularly in the wheel mechanism[6]. In future work, the dimensions of RollerBall could therefore be reduced by using smaller DC motors (also available from Maxon).

The individual mechanisms function as intended. The arms can be adjusted rapidly and can provide the required force, despite expected inefficiencies in the mechanism and the conservative friction coefficient used in the calculations. The rotational speed of the wheels is much greater than the requirement and could allow high linear speeds even if slip occurs *in vivo.* The maximum tractive effort of each wheel is well above the required 0.33 N and thus propulsive force is limited only by the wheels' ability to gain traction.

Tests in the variable diameter tube showed that the orientation of RollerBall can be controlled in both an expanded and collapsed robot state (the latter is not shown). It is important to maintain an axial, forward-facing orientation in the tube during tests to prevent the front of the device from catching on the lumen and stopping progress. This requires the user to make continual fine adjustments to the orientation. The lack of force feedback means that it is also difficult to assess when to alter the angle of the arms. Despite these issues, the robot provides a stable platform while moving from one aperture to another.

Tests in the second tube demonstrated the mobility of RollerBall as it successfully traversed bends of increasing acuteness. Unsuccessful cornering was attributed to the length of the body and the high friction between it and the silicone tube. If the angle of approach was suboptimal, the device became wedged in the corner and required considerable maneuvering to free it. The friction between the device and the lumen may not be an issue *in vivo* because of the low friction of the colonic mucosa. A reduction in the overall size of the device will also improve mobility around bends.

RollerBall is currently controlled using only visual feedback. The use of DC motors means that very precise movements can be made by intuitive adjustments of the analogue joysticks and triggers. However, the fact that the user is required to simultaneously control speed, orientation and arm angle means that controlling the robot, particularly around bends, is challenging. Precise, manual control is particularly difficult when the device rolls because this changes the user's axis of reference[7]. The issue of the lack of automation is highlighted by the slow average movement speed in both tubes: 4.9 ± 1.7 mm/s (n = 5) in the first tube and 3.6 mm/s (n = 1) in the second tube. Despite these low values, the speed broadly meets the requirements. Comparatively, when little user input was required (in a straight section of tube, for example), peak speeds of ca. 22 – 29 mm/s were recorded. The inclusion of embedded sensors and a camera could permit automated closed-loop control of arm expansion and device orientation. This is expected to significantly reduce the demand on the user and greatly increase the overall movement speed. A forward facing camera and force feedback would also mean that the robot could operate in a non-transparent tube.

It is important to acknowledge the limitations of the test environment. The scale used was somewhat larger than that found *in vivo*. While the morphologies only approximate the complexities of the colon, they do allow an assessment to be made of the device's basic functionality. More extreme diameter changes are expected *in vivo*, as are more acute bends and the presence of surface ridges (haustral folds). Silicone was used for these tests as it provides a robust, reusable environment that is both flexible and transparent. Other authors have shown that tread patterns are effective on intestinal tissue and so to simplify testing, traction was not assessed in this study. Lastly, it is intended for RollerBall to be used in a flooded environment. This is likely to be advantageous in providing a well distended colon and a denser medium that could help support the device. A disadvantage could be reduced traction and the need for water-tight encapsulation.

[6] Assuming 0.66 N tractive effort per wheel (twice the desired), the motor provides ca. 350 % more torque than required.

[7] Steering the device using the image from an on-board, forward facing camera will likely alleviate this problem as the view (image) is fixed to the axis of the robot.

VII. Conclusion

Current work on RollerBall has shown the feasibility of the concept in the context of a flexible, synthetic lumen. It can provide a stable platform in varying diameters and the position and orientation can be intuitively controlled. As a result, work has begun on developing the concept further.

Future work will include:

- Development of an advanced, semi-autonomous control system with sensor feedback. This could improve the usability and aid in making the device atraumatic.
- Device miniaturization to further improve mobility and reduce trauma.
- Comprehensive evaluation of the traction performance of various tread patterns on colon tissue.
- More advanced, rigorous tests in an environment created using *ex vivo* tissue. This could allow for a more realistic assessment of the device's usability and overall efficacy.
- Development of on-board diagnostic tools. These could include a forward facing camera, light source and biopsy tool.

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References

[1] D. Gavin, R. Valori, J. Anderson, M. Donnelly, J. Williams and E. Swarbrick, "The national colonoscopy audit: a nationwide assessment of the quality and safety of colonoscopy in the UK." Gut, 2013, vol. 62, pp. 242-249.

[2] R. Siegel, C. DeSantis and A. Jemal, "Colorectal Cancer Statistics, 2014." CA: A Cancer Journal for Clinicians, 2014, vol. 64, pp. 104–117.

[3] S. Gurudu. and F. Ramirez, "Quality measurement and improvement in colonoscopy." Techniques in Gastrointestinal Endoscopy, 2012, vol. 14, pp. 21-28.

[4] G. Ciuti, A. Menciassi, and P. Dario, "Capsule Endoscopy: From Current Achievements to Open Challenges." Biomedical Engineering, IEEE Reviews in, 2011, vol. 4, pp. 59-72.

[5] S. Gomez, M. Llinas, A. Garangou, C. Garcia, J. Alsina, J. Gibert, J. Colella and C. Colella, "Dark-lumen MR colonography with fecal tagging: a comparison of water enema and air methods of colonic distension for detecting colonic neoplasms." European Radiology, 2008, vol. 18, pp. 1396–1405.

[6] F. Leung, A. Amato, C. Ell, S. Friedland, J. Harker, YH. Hsieh, J. Leung, S. Mann, S. Paggi, J. Pohl, F. Radaelli, F. Ramirez, R. Siao-Salera and V. Terruzzi, "Water-aided colonoscopy: a systematic review," Gastrointestinal Endoscopy, 2012, vol. 76, no. 3, pp. 657-666.

[7] W. Lin, Y. Shi, Z. Jia and G. Yan, "Design of a wireless anchoring and extending micro robot system for gastrointestinal tract," The International Journal of Medical Robotics and Computer Assisted Surgery, 2013, vol. 9, pp. 167–179.

[8] M. Quirini, A. Menciassi, S. Scapellato, C. Stefanini and P. Dario, "Design and Fabrication of a Motor Legged Capsule for the Active Exploration of the Gastrointestinal Tract." IEEE Transactions on Mechatronics, 2008, vol. 13, no. 2, pp. 169-179.

[9] H. Kim, S. Yang, J. Kim, S. Park, J. Cho, J. Park, T. Kim, E.S. Yoon, S. Song and S. Bang, "Active locomotion of a paddling-based capsule endoscope in an in vitro and in vivo experiment," Gastrointestinal Endoscopy, 2010, vol. 72, no. 2, pp. 381–387.

[10] A. Arezzo, A. Menciassi, P. Valdastri, G. Ciuti, G. Lucarini, M. Salerno, C. Natali, M. Verra, P. Dario and M. Morino, "Experimental assessment of a novel robotically-driven endoscopic capsule compared to traditional colonoscopy." Digestive and Liver Disease, 2013, vol. 45, no. 8, pp. 657-62.

[11] A. Alazmani, A. Hood, D. Jayne, A. Neville and P. Culmer, "Quantitative Assessment of Colorectal Morphology: Implications for Robotic Colonoscopy," Medical Engineering and Physics, 2016. (In Press).

[12] I. Kassim, L. Phee, F. Gong, P. Dario and C. Mosse, "Locomotion techniques for robotic colonoscopy." IEEE Engineering in Medicine and Biology Magazine, 2006, pp. 49-56.

[13] F. Paparo, A. Garlaschi, E. Biscaldi, L. Bacigalupo, L. Cevasco, G. Rollandi, "Computed tomography of the bowel: A prospective comparison study between four techniques." European Journal of Radiology, 2013, vol. 82, pp. e1-e10.

[14] K.D. Wang. and G.Z. Yan, "Research on measurement and modeling of the gastro intestine's frictional characteristics." Measurement Science and Technology, 2009, vol. 20, pp. 015803 (6pp).

[15] S.H Lee, Y. Kim, S. Yang, E. Yoon, D. Kim and K. Suh, "An optimal micropatterned end-effecter for enhancing frictional force on large intestinal surface." ACS Applied Materials and Interfaces, 2010, vol. 2, no. 5, pp. 1308-1316.

[16] E. Buselli, V. Pensabene, P. Castrataro, P. Valdastri, A. Menciassi and P. Dario, "Evaluation of friction enhancement through soft polymer micro-patterns in active capsule endoscopy." Measurement Science and Technology, 2010, vol. 21, no. 10, pp. 105802 (7pp).

[17] P. Glass, E. Cheung, and M. Sitti, "A legged anchoring mechanism for capsule endoscopes using micropatterned adhesives," IEEE Transactions on Biomedical Engineering, 2008, vol. 55, no. 12, pp. 2759–2767.

[18] P. Gao, G. Yan, Z. Wang, P. Jiang and H. Liu, "Microgroove cushion of robotic endoscope for active locomotion in the gastrointestinal tract." International Journal of Medical Robotics and Computer Assisted Surgery, 2012, vol. 8, pp. 398–406.