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Design of a Pill-Sized 12-legged Endoscopic Capsule Robot

Marco Quirini, Robert J. Webster III, Arianna Menciassi, and Paolo Dario.

Abstract—**In this paper we present the design of a swallowable (11mm diameter by 25mm long), 12-legged endoscopic capsule for locomotion in the lower gastro intestinal tract (large bowel). A novel slot-follower mechanism driven via lead-screw allows the capsule to be as small as current commercial pill-cameras, while simultaneously generating 2/3 N of force at each leg tip. Kinematic and static analyses of the lead screw and slot-follower mechanisms allow optimization of design parameters so that the capsule satisfies experimental and clinical design requirements for legged locomotion in the GI tract.**

I. INTRODUCTION

Endoluminal devices for minimally invasive surgical and/or diagnostic applications have recently begun to show great promise for improving treatment of various diseases [1-5], particularly in the lower gastrointestinal (LGI) tract [6-8]. These LGI tract devices lack of active locomotion, moving by simply exploiting GI peristalsis (the natural muscle activity that causes food to move along the GI tract). Consequently they cannot stop, turn, or reverse direction. Nevertheless they have proven clinically beneficial for diagnoses in the small intestine, which is extremely difficult to access without them.

Other devices have been designed to locomote in the colon based on a variety of techniques [9-11], but they do so against peristalsis, and since they are not swallowable, cannot eliminate the hospital visit associated with standard colonoscopy.

The ideal system for LGI tract access would combine the most beneficial elements of both the pill-cameras (being small enough to swallow and moving in the direction of natural peristalsis), as well as actively locomoting devices (ability to move as desired), while not requiring inflation of the colon (the source of much of the pain associated with the procedure). If such a system could allow colonoscopy to become a self-administered procedure, it would significantly improve public health by improving cancer screening. Cancer deaths per year has increased sixfold from 1930 to 2003 [12], with many deaths preventable by early diagnosis. The capsule described in this paper is a step toward this ideal system, enabling legged locomotion in a pill-sized device. Our slot-follower/lead screw mechanism additionally improves on the state of the art in legged capsule technology by including more legs than has been possible before, which is expected to be useful for both distending deflated colon tissue and also for navigating the sharp corners of the splenic flexure found in the colon. Our design also allows for novel capsule gaits to be developed, since our slot-follower mechanism enables both adjustment of leg attachment points and also permits legs to open at different rates.

A. *Locomoting Endoscopic Capsules*

The goal of a locomoting capsule for the small intestine has been in part approached via magnetic fields. RF Norika [13] has proposed an endoscopic pill with power supplied by an external wireless system, which may be able to rotate if stimulated by external magnetic fields. They intend to attempt to embed power and magnetic sources in a jacket, which patients would wear during an examination. A similar device, designed to both rotate and translate backward and forward, is being developed by Olympus [14]. It is also possible to include a permanent magnet within the capsule [15] to increase the forces applied to the capsule by the external field. Electrical stimulation to induce peristalsis has also been suggested as an alternative to magnetic actuation [16-17], but this approach lacks the ability to reverse the direction of travel. Additionally, none of the above has been designed to function in both the large and small intestines.

While locomoting robots able to move inside tubular structures are commonly used in industrial or civil fields (e.g. for pipe inspection, as described in [18-22]), developing robotic capsules able to move inside the GI tract is more challenging. This is due to the unstructured nature of the environment, which has loose, elastic, slippery walls [23-25]. For this reason traditional locomotion systems such as wheels appear unsuitable for the intestine.

However, some other locomotion systems have been developed for integration into biomedical devices, such as the rotating rib used in [26]. Other locomotion methods that have been attempted for propulsion inside body cavities include a fin type electromagnetic actuator [27], a multi-joint endocavitary robot actuated by piezoelectric elements [28], and a robotic capsule with four actuators, based on two shape memory alloy (SMA) springs, able to linearly move four clampers along the capsule body [29]. The endoscopic capsule described in [30-32] also exploits SMA for performing legged locomotion inspired by cockroach locomotion.

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R. J. Webster, III is with the Johns Hopkins University Department of Mechanical Engineering, 223 Latrobe Hall, 3400 North Charles Street, Baltimore, Maryland 21218 USA (e-mail: robert.webster@jhu.edu).

Marco Quirini, Arianna Menciassi, and Paolo Dario are with the CRIM Lab of Scuola Superiore Sant'Anna Pisa, Italy (corresponding author to provide phone: +39-050-883028; fax: +39-050-883496; e-mails:marco.quirini@sssup.it, arianna@sssup.it, dario@sssup.it).

II. REQUIREMENTS AND DESIGN OVERVIEW

Medical considerations provide design requirements for capsule robots such as size, speed, and safety However, doctors usually provide general objectives rather than the detailed specifications required to perform an engineering design. Our extensive previous experience with design and testing of other capsule robots [30-32] enables us to translate these general medical requirements into useful engineering specifications.

A. Medical Considerations

Size. In order to be swallowable, a capsule robot must fit within a cylindrical shape 11mm in diameter by 26mm in length – the size of commercial pill-cameras such as the Olympus capsule [14], that have been demonstrated swallowable and are currently undergoing clinical trials.

Speed. A standard colonoscopy is completed in approximately 20 min-1 hour [37], so it is desirable for a locomoting robot to be able to move fast enough to travel through the colon in this time. An alternative time criteria may be possible if the capsule is intended to be used at home, while the patient sleeps. There is an average of approximately 7 hours of sleep-time in which the capsule could work. However, we use a 1-hour colonoscopy timeframe as a general criterion for capsule motion.

Safety. The capsule's contact with the walls of the LGI tract should cause no more damage than a standard colonoscope.

Painless. Air insufflation exploited during standard colonoscopy causes abdominal pains for the patient; for this reason the capsule has to be provided with a locomotion system able to propel the capsule forward without insufflation.

Functionality. At a minimum, doctors need to visually observe the interior of the LGI. The next step beyond this in terms of clinical impact is obtaining a biopsy sample, while futuristic goals include actual interventions and treatments carried out by the capsule robot itself.

B. The Legged Solution

As outlined in previous sections, a variety of locomotion strategies have been proposed for the gut. However, to prove clinically useful, any strategy chosen for a capsule robot must address the specific challenges of this environment as outlined in [24], and must be capable of locomotion on a slippery and deformable substrate. The gut is an extremely compliant, non-linear, visco-elastic material, typically covered by a thick (up to 2 mm) layer of lubricant mucus, with a friction coefficient as low as 10^{-3}. Taking into account the guidelines provided by [24], a legged locomotion system appears to have many advantages [30].

Regarding safety, we have experimentally evaluated the legged solution on 4 and 6 legged capsule robots in *in-vivo* porcine models [33-35]. In these tests it was observed that while the leg tips can sometimes create light red marks on the colon wall, these marks are less severe than those that can be caused by scratching as a standard colonoscope is pushed into the colon. This qualitative judgment about the severity of marks left by the capsule feet was rendered by an expert surgeon experienced with colonoscopy [39].

C. Force Requirements and Actuator Selection

Extensive experience testing and modeling [33-36] legged capsules has revealed approximately for a 12-legged capsule robot designed as outlined in following sections, 2/3 Newton is an upper bound for the force required at each foot to propel the capsule along the LGI This makes actuator selection very difficult, because of the long lever arm of the leg (see $b_{1,max}$, $b_{2,max}$ and $b_{3,max}$ in Table III) outside the body, compared to the short lever arm within, require relatively high forces in a very compact package. Thus the actuator must be the first design consideration, and the rest of the capsule designed around it. While attempts have been made to use SMA [32], these actuators have high power consumption and low bandwidth, since they must be heated to produce motion.

The actuator selected by the authors (the only one we are aware of that is feasible given our design requirements) is a DC brushless motor developed by the Namiki Precision Jewel Co., Ltd. It has an external diameter of 4 mm and a total length of 16.2 mm (gearhead included), with a maximum output torque of 0.058 mNm. With the inclusion of the 79:1 gearhead, the output torque of the motor is amplified to 2.92 mNm. While it is possible to find smaller commercial actuators, their output torque and speed characteristics are generally insufficient for the legged locomotion task. Namiki Precision Jewel Co., Ltd, provides a full control system based on a brushless motor controller (LB1981 from Sanyo) which allows controlling the motor from outside by simply using two pins (while other two pins are used to powering the controller board). This control is not integrable on capsule due to its dimensions (34.4mm x 19.6mm). For this reason the authors are developing an electronic board with a microcontroller (ATMEL ATMega 48) small enough (5mm x 5mm) to be embedded in the capsule body. The power consumption of the actuator (together with its driver) is about 300 mW.

D. Leg Placement and Gait

Once the legged locomotion strategy and actuators have been selected, the next set of questions to be answered are the number of legs to use, the gait they should follow, and their placement positions on the capsule wall. One possible combination of these parameters that permits locomotion has been described for a 6-legged capsule in [33]. However, as will become clear shortly, the slot-follower/lead screw design of our 12-legged capsule permits some additional freedom in leg placement, as well as enabling legs to open at different rates and to different maximum angles.

Number of legs. It seems desirable to maximize the number of legs on the capsule for two reasons. First, more legs distribute the force needed to propel the capsule over more points of contact, reducing the individual foot force and potential for tissue irritation at each foot. Second, more points of contact are expected to improve the propulsion of the capsule in the folded, loose, highly deformable, unstructured environment of the colon. They are also useful for distending the colon as mentioned earlier, and may assist in negotiating sharp corners such as the splenic flexure.

Gait and Leg Position on Capsule. It has been shown that successful locomotion is possible with two sets of legs, one in the front and one in the rear capsule [33], and we adopt this general strategy. With the gait outlined in [33], the rear set of legs has the primary function of producing thrust force, while the frontal set is used for the dual purposes of fixing the capsule in his position (when the rear legs release contact with the wall) and also to help steer the capsule around curves.

Figure 1 illustrates the disposition of the two sets of legs.

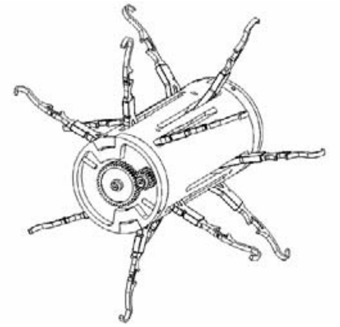

Figure 1. Iso view of the 12-legged capsule.

Leg Tip Placement. Extensive testing has revealed that the total diameter of the circle created by the leg tips when open should be approximately 30-35 mm for locomotion in the colon. Looking end-on at our capsule, Figure 2 shows how the 12 leg tips are positioned at near-equal angular intervals around the 32 mm circle, despite motors preventing similar equal spacing within the capsule. The only exception to the equal placement of leg tips are the legs farthest from the motors (nearest the horizontal plane in Figure 2). These four legs were shifted away from the horizontal plane by 4 degrees each (only 1.1 mm tip displacement from ideal position), to prevent their interfering with one another when folded within the capsule.

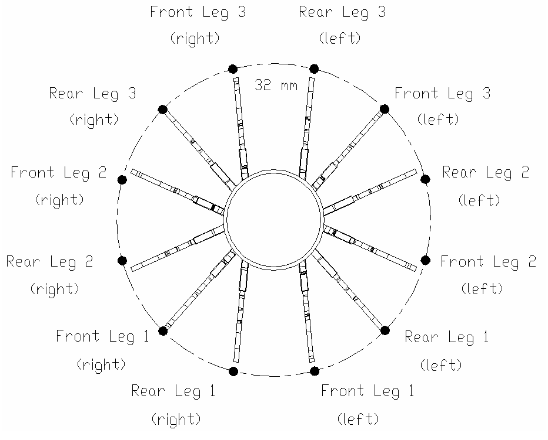

Figure 2. Front view of the capsule showing a 32 mm diameter circle (suitable for engaging and distending – but not perforating – the colon wall) and the leg tips near-equally distributed around the circle.

E. The Slot-Follower/Lead Screw Actuation Mechanism

Figure 3 shows a view of the internal mechanism of the capsule. The motor drives a gear attached to the miniature lead screw. As the screw spins, it translates the nut linearly. The leg-holder is fixed to the nut with a pin that permits it to rotate as the nut moves. At the capsule wall is another pin, inserted into a slot in the leg-holder (this is the slot-follower mechanism). As the nut translates back and forth, the tip of the foot on the leg makes a stride. All 6 legs at a given end of the capsule are attached to one nut, and all simultaneously open and close as the nut translates.

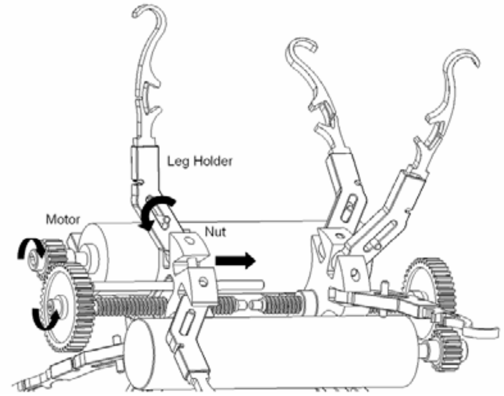

Figure 3. Side view of the capsule showing motor, gears, lead screw, leg-holder, leg and pins. The arrows show the direction of translation of the nut and the rotational movement imparts to the leg-holder.

III. KINEMATIC ANALYSIS AND OPTIMIZATION

While there are many constraints to consider when designing the slot-follower mechanism, there remain a family of possible solutions that permit novel gait patterns, as well as some freedom of leg placement on the capsule exterior.

We present a solution here that strikes a balance between many competing design objectives, while optimizing leg opening angles. However, we note that the slot-follower design permits future studies (in simulation or experimentation) to test new gait patterns and leg placements. The following analysis provides the set of possibilities in which such an optimization can be conducted.

First, however, the design constraints must be defined. They are as follows:

1. The overall size must be at most 11 mm diameter by 26 mm in length, and contain two motors, which each consume take 10.5 % of this space.
2. Leg opening angles must be at least 110 degrees to permit good contact with the LGI walls (this constraint is based on our prior experience with legged capsules).
3. We require a maximum possible foot force of 2/3 N [36]. This implies that the pins in the mechanism must be far enough from one another so that the motor can generate sufficient torque to actuate the mechanism with the desired foot forces.
4. Legs must all simultaneously retract within the capsule when in the closed position so that the capsule can be swallowed.
5. All components must be sufficiently large and thick enough to withstand the forces they will experience.

Figure 4 shows the geometry of the slot-follower mechanism. While each of the two nuts (one at each end of the capsule) holds six legs, the dimensions of only three on one side of the nut need be designed because the other three on the opposite side are identical copies of the first three, but rotated by 180 degrees about the central nut axis.

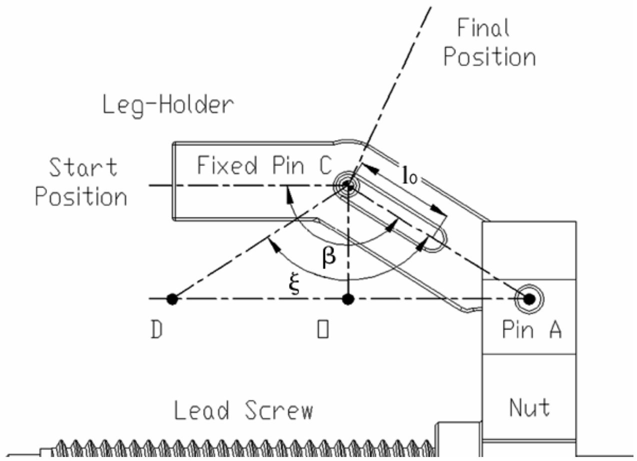

Figure 4. Side view of the slot-follower mechanism showing all its design parameters.

The first design decision is the length of OC$_i$, $i \in \{1, 2, 3\}$, because many of the above-listed constraints influence it. While constraint (3) provides a test for minimum possible lengths of OC$_i$, it is generally desirable to make each OC as long as possible to reduce mechanism internal forces. Too long, however, and constraint (2) is violated (as will be further described shortly). In the presence of size constraints (1) and (5), we choose the longest feasible lengths for the OC$_i$ values and proceed with further analysis using these fixed values.

The AD distance will be the same for all legs at a given end of the capsule, because all are attached to the same nut. The maximum possible AD distance, fixed by constraints (1) and (5), is approximately 6.2 mm. The OD$_i$ distances may be selected to place the legs at desired positions on the outside of the capsule, but OD$_i$ must be no more than AD/2 as illustrated in Figure 5.

The values AD, OD, OC and ξ_i are related by the law of cosines:

$$\xi = cos^{-1}\left\{\frac{\overline{AD}\cdot\overline{OD}-\overline{OC}^2-\overline{OD}^2}{\left[\left(\overline{AD}-\overline{OD}\right)^2+\overline{OC}^2\right]^{\frac{1}{2}}\left[\overline{OD}^2+\overline{OC}^2\right]^{\frac{1}{2}}}\right\} \tag{1}$$

Figure 6 explores permissible possible AD and OD$_i$ combinations. The regions above the plane do not violate constraint (2), and any set of points that share a common AD and are on the three surfaces and above the plane may be used to select OD$_i$ values. Selection of OD$_i$ is equivalent to selecting the position on the outside of the capsule where the legs will be attached. We choose them to maximize the angle to which the legs can open (ξ_i), meaning OD$_i$ = AD/2. All the resulting calculated values are listed in Table I.

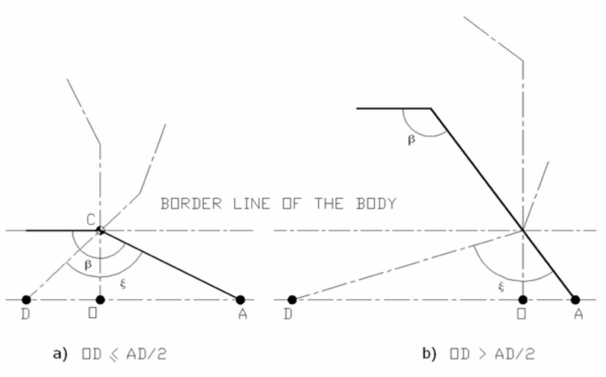

Figure 5. a) In the closed position (dark line) the leg is completely inside the body (indicated by the body border line). b) In this case in the “closed” position the leg remains outside the body.

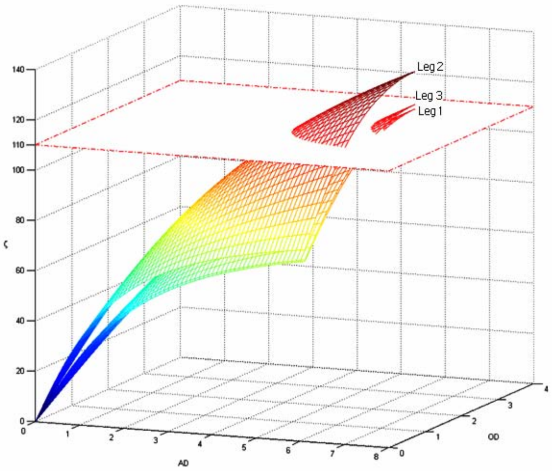

Figure 6. The Matlab plot showing the permissible AD and OD$_i$ combinations, providing a design tool for both leg opening angles and leg placement positions on the outside of the capsule body. The points above the plane on the surfaces do not violate constraint (2). Additionally, all three legs must share a common AD (total nut displacement) value.

TABLE I
PARAMETERS OF SLOT-FOLLOWER MECHANISMS

	Leg 1	*Leg 2*	*Leg 3*
AD [mm]	*6.20*	*6.20*	*6.20*
OC [mm]	*2.03*	*1.50*	*1.96*
OD [mm]	*3.10*	*3.10*	*3.10*
ξ [°]	*113.57*	*128.37*	*115.32*
β [°]	*146.78*	*154.19*	*147.66*
l_0 [mm]	*1.68*	*1.94*	*1.70*

IV. FORCE ANALYSIS AND LEAD SCREW DESIGN

The actuation mechanism described above was dimensioned in conjunction with a consideration of the force requirements at the leg tips. Here, we provide an analysis of the forces and torques in all parts of the lead screw/slot-follower mechanism, to ensure that the actuators are capable of providing the desired foot forces *F*.

A. Converting Foot Force to Lead Screw Force

As mentioned previously, we estimate $F = 0.66$ N per foot as the maximum necessary for a 12-legged capsule to locomote in the intestine. Each foot force produces a reaction force at the nut (amplified by the lever between the pins as shown in Figure 7) of:

$$R_i = F\frac{b_{i,\max}}{a_i} \quad i \in \{1, 2, 3\} \tag{2}$$

The values $b_{i,max}$ are the maximum possible lever arms between the pin at the capsule wall and the tip of the leg. The value of $b_{i,max}$, as well as the corresponding position of the nut when it occurs are somewhat involved calculations, and are contained in the Appendix. For current purposes, it is enough to say that they will be in the range of 11.7 - 12.2 mm, depending on the leg.

The summation of these 6 reaction forces on the nut,

$$W = 2 \times \sum_{i=1}^{3} (R_i), \tag{3}$$

is the total linear force that the lead screw must provide when the legs are in their worst-case configurations and simultaneously loaded with maximum foot forces. Note that this configuration is not quite physically realizable, since the legs open at different rates due to the different OC distances. Therefore, all feet cannot simultaneously achieve their longest possible lever arms. However, considering Equations (1) and (2) as written, the calculation is conservative. It will yield a slightly higher torque required from the actuators than the worst-case physically realizable configuration requires.

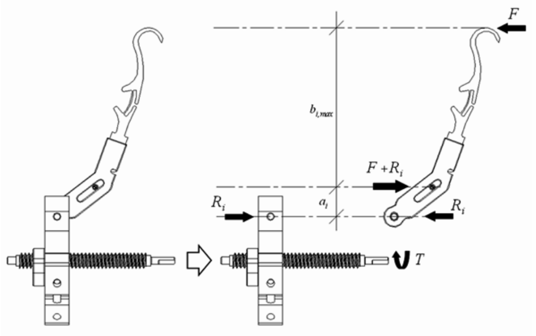

Figure 7 A Free body diagram of the mechanism showing forces and torques.

The torque which must be applied to the lead screw to overcome W is given by the standard lead screw equation:

$$T = \frac{W d_m}{2} \frac{\mu \pi d_m + L\cos\alpha_n}{\pi d_m \cos\alpha_n - \mu L} \tag{4}$$

where d_m is the pitch diameter of the screw, μ is the coefficient of friction between the lead screw and the nut, α_n is the cross section angle of the thread (measured in a plane perpendicular to the helical profile of the screw) and L is the axial pitch of the screw. The lead screw is connected to the DC motor through a gear reduction with a ratio of 0.425 as shown in Figure 3.

B. Lead Screw Design

The lead screw has three parameters that may be designed to meet the device specifications: pitch diameter d_m, the axial pitch L, and the coefficient of friction μ.

It is desirable to use standard screw sizes to simplify manufacture of the nut, since it is possible to purchase standard taps to cut the internal threads of the nut for standard screw sizes. Thus, each standard d_m size has a corresponding pitch.

The coefficient of friction can be designed by choosing appropriate materials for the nut and lead screw. For example, a lubricated steel-steel surface has a coefficient of 0.11 ÷ 0.17 [38], and a bronze nut on a steel screw has a coefficient of 0.10 ÷ 0.15 [38].

As the best possible tradeoff between speed and force considerations, we selected a 1 mm diameter lead screw (d_m = 1 mm), with the standard pitch of 0.25 mm/turn. To minimize the friction it is desirable to make our nut from bronze and our lead screw from steel. However, we plan to carry out further studies to ensure that a bronze nut will be able to withstand the forces the pins apply to it without damage. All the selected design parameters and resulting calculated values for our capsule are listed in Table II.

TABLE II
DESIGN PARAMETERS OF THE LEAD SCREW

T [Nmm]	3.48	d_m [mm]	1
R_1 [N]	3.81	L [mm]	0.25
R_2 [N]	5.36	α_n [°]	14,44
R_3 [N]	3.96	μ	0.17
W [N]	26.27		

Note that the value of torque required by the motor is within its 2.9 mNm specifications. Under full load (0.66 N), the legs will move rather slowly, at 18 mm/min. Since one opening and closing cycle requires two travels of the nut over its 6.2 mm range, at this expected average speed, one leg cycle can be completed in 21 sec. However, the legs will rarely reach full load, even when engaging the colon wall, and there will be large portions of their duty cycle when b is small or there is no foot-tissue contact. Thus the average foot force we expect over the full stride is less than 0.66 N, meaning that the nut should ordinarily be capable of moving at higher speed. Note also that all calculations in this paper are conservative because they are based on considering rigid legs. The legs of the capsule will in fact be flexible (made of Nitinol as in [33]), and provided with a flexure-based joint at the knee (also made of Nitinol as in [33]). Our estimate of required foot forces takes both leg flexibility and the knee joint into account, since it is based on experimentation similar jointed legs. Thus, there is no doubt that these legs will not interfere with the capsule's ability to locomote. The flexibility of the knee can only be beneficial, making our all calculations in this paper conservative and reducing all internal mechanism forces calculated in this paper, further improving capsule speed.

V. CONCLUSION

The slot-follower/lead screw mechanism presented in this paper enables miniaturization of a legged endoscopic capsule to a swallowable size and simultaneously supports 12-legs. The prospect of making such a capsule swallowable holds great promise for improving patient comfort and safety during colonoscopies (and even potentially delivering treatment at the same time as screening), and might thereby increase the number of people in the targeted screening group who actually have the procedure done. If this happens, the result will be identifying many more cancers in very early stages, thereby improving public health and reducing the cost of treatment. However, making the capsule swallowable requires it to locomote in an uninflated colon (in standard colonoscopy, the colon is inflated before the endoscope is introduced), which introduces new challenges for the capsule robot to overcome.

We expect the large number of legs in our capsule to improve locomotion in this uninflated environment by

1. distending the tissue;
2. providing a better chance of more feet finding good footholds in the slippery, folded, deformable environment;
3. spreading the force required for locomotion over more points of contact, reducing foot-tissue interaction force and thus reducing tissue damage.

Our design also provides an environment for optimization of gaits, because there is some freedom with regard to placement positions of the legs are placed on the capsule wall, and also the legs are able to open and close at different rates (designable by changing OC distances).

In the near future a prototype of the capsule will be manufactured and tested in *in-vitro* and in *ex-vivo* models.

APPENDIX: MAXIMUM LEG LEVER ARMS

The maximum value of the lever arm b_i has been estimated considering the position of the nut for which the maximum distance of the leg tip from the fixed pin *C* occurs (see Figure 4).

Considering the schematic shown in Figure 8, we can write:

$$b_i = y_{E,i} - h \,, \tag{5}$$

where,

$$\begin{aligned} y_{E,i} = \; & \sin\vartheta\left(\mathrm{l}_{0,\mathrm{i}} - \mathrm{l}_{2,\mathrm{i}}\cos\beta_i\right) - l_{2,i}\sin\beta_i\cos\vartheta + \\ & + L_g\cos\left(\frac{3}{2}\pi - \beta_i - \vartheta\right), \end{aligned} \tag{6}$$

where $y_{E,i}$ is the value of the distance of the tip of i$^{\text{th}}$ leg from horizontal axis during the motion of the mechanism. In addition $l_{0,i}$ is the length of the first segment of the i$^{\text{th}}$ leg holder (the distance AC before the bend), $l_{2,i}$ is the length of the second segment of the i$^{\text{th}}$ leg holder (the distance CS after the bend), L_G is the length of the i$^{\text{th}}$ leg, β_i is the bend angle of the i$^{\text{th}}$ leg holder and ϑ is the angle between the i$^{\text{th}}$ leg holder and the x axis in Figure 8 at the point that travels along the axis.

Differentiating equation (6)

$$\begin{aligned} \frac{dy_{E,i}}{d\vartheta} = & \cos\vartheta\left(\mathrm{l}_{0,\mathrm{i}} - (\mathrm{l}_{2,\mathrm{i}} + \mathrm{L}_\mathrm{G})\cos\beta_i\right) \\ & + (l_{2,i} + L_G)\sin\beta_i\sin\vartheta + = 0, \end{aligned} \tag{7}$$

we obtain the maximum value of the distance between the leg tip and the horizontal axis. This is given by,

$$\vartheta_{\mathrm{i,max}} = \arctan\left[-\frac{\left(\mathrm{l}_{0,\mathrm{i}} - (\mathrm{l}_{2,\mathrm{i}} + \mathrm{L}_\mathrm{G})\cos\beta_i\right)}{(l_{2,i} + L_G)\sin\beta_i}\right]. \tag{8}$$

Replacing $\vartheta_{i,max}$ in eq. (6) with this result, we obtain the desired value of $y_{E,i\ max}$, and thus the value of $b_{i,max}$ using eq. (5). Finally the corresponding position of the nut along the longitudinal axis is given by:

$$\mathrm{x_i} = \mathrm{l_1} - \frac{h}{\vartheta_{\mathrm{i,max}}} \tag{9}$$

All the resulting calculated values are reported in Table III.

TABLE III
MAXIMUM LEVER ARM CALCULATION PARAMETERS

Leg 1		*Leg 2*		*Leg 3*	
$b_{1,max}$[mm]	*11.721*	$b_{2,max}$[mm]	*12.183*	$b_{3,max}$[mm]	*11.778*
$\vartheta_{1,max}$ [°]	*114.73*	$\vartheta_{1,max}$ [°]	*109.52*	$\vartheta_{3,max}$ [°]	*114.13*
x_1 [mm]	*4.035*	x_2 [mm]	*3.820*	x_3 [mm]	*4.009*

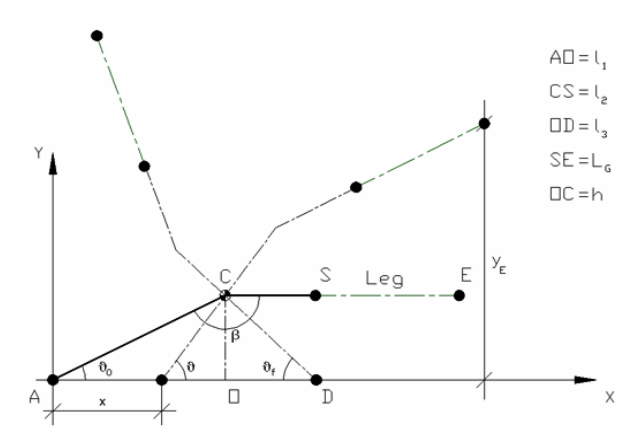

Figure 8. Line schematic of slot-follower mechanism used for calculating the position where the leg tip reaches maximum distance from the capsule wall.

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