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Towards active capsular endoscopy: preliminary results on a legged platform

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Abstract— **This paper illustrates the problem of active locomotion in the gastrointestinal tract for endoscopic capsules. Authors analyze the problem of locomotion in unstructured, flexible and tubular environments and explain the reasons leading to the selection of a legged system. They present a theoretical simulation of legged capsule locomotion, which is used to define the optimal parameters for capsule design and gait selection. Finally, a legged capsule - about 3 cm^3 in volume - is presented; it consists of 4 back legs whose actuation is achieved thanks to a miniaturized DC brushless motor. In vitro tests demonstrate good performance in terms of achievable speed (92 mm/min).**

I. INTRODUCTION

ENDOSCOPY and endoluminal surgery are becoming a concrete alternative to most medical problems and pathologies, and the development of new generations of advanced and miniaturized endoscopic tools is mandatory to foster this medical and technological sector. In particular, the development of endoscopic capsules provided with active locomotion systems is fundamental in order to improve gastrointestinal painless endoscopic procedures.

By introducing an active locomotion system into passive endoscopic an active endoscopic device allows to explore the whole gastrointestinal (GI) tract - including areas that normally are not reachable by traditional endoscopic procedures, such as the small intestine -, to reduce the training process and the learning phase of the endoscopist - thanks to the ability of the endoscopic device to move autonomously in the GI tract -, to screen all population, including no-symptomatic people, thanks to a procedure which has the potential to be painless.

Basically, two wireless endoscopic capsules are commercially available currently: the M2A [1] capsule system developed by Given Imaging, Ltd. and the endoscopic capsule developed by Olympus Medical Systems Corporation [2]. These devices do not possess any active locomotion capabilities and they exploit natural gastrointestinal peristaltic waves to move forward. The limit of this kind of locomotion strategy - passive locomotion - is related to the impossibility of stopping and modifying capsule motion during the GI travel. In fact, capsule movement controllability is an essential requirement in order to detect, observe and analyze on pathological areas and to perform medical procedures like biopsy and drug delivery. A teleoperated microcapsule provided with active locomotion system would be able to accomplish these tasks thanks to the ability to stop, turn and reverse its course in the GI tract.

II. SELECTION OF LOCOMOTION STRATEGY

The first step which must be done in order to develop a capsule provided with an active locomotion system is the selection of a suitable locomotion strategy, which allows the robot to propel in the gut; on the other hand, the locomotion strategy is strictly connected to the features of the GI tract in which the device must work.

A preliminary analysis of the locomotion issues in the gut has been performed by the authors in [3] and [4], where it has been outlined how an effective locomotion in a slippery and deformable substrate – such as the human gut – must take into account the biomechanics of the tissue, which is an extremely compliant non-linear viscoelastic material typically covered by a thick (up to 2 mm) layer of lubricant mucus. Taking into account the guidelines provided by this preliminary studies, the active locomotion system the authors have selected is based on a set of miniaturized legs. This solution draws inspiration from cockroach's locomotion systems: cockroaches show remarkable locomotion abilities in a wide variety of terrains, especially in unstructured terrains, and their size is compatible with the size of a swallowable device (i.e. a few cubic centimetres) [5], [6].

A legged locomotion system offers many advantages in terms of: (1) good control on the trajectory which allows the capsule to pass over critical areas without touching them; (2) better adaptability to the environment: thanks to legs, the capsule is suitable to propel in anatomically and biomechanically different areas (stomach, small and large intestine) featured by different average diameter; (3) simplified adhesion: by localizing the contact points in small areas (tip of each leg) larger contact pressures can be

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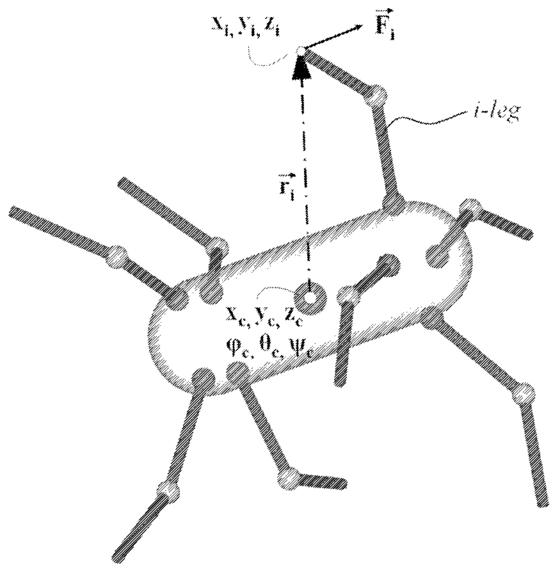

Fig. 1: Legged capsule model. Each leg has multiple degrees of freedom both at ankle and knee joint. Absolute position of each leg tip can be expressed as composition of joints coordinates and capsule positioning (orientation + position of the center of mass).

reached, thus producing significant local deformation. In this way high friction coefficient can be reached in the contact points, thus improving the lever effect.

According to the authors a locomotion system able to propel an endoscopic device in the gut should be provided with:

- at least 2 set of legs, one in the front and on in the back part, are necessary for locomotion; one set of legs has the function to produce a thrust force in order to propel;
- at least one active degree of freedom (DoF), moving the leg in the longitudinal direction along the capsule body, and one passive DoF at the leg knee, adjusting the leg to the compliance of the tissue, are necessary. It should be noticed that the ability of the capsule to propel itself in the gut is strictly related to the number of active DoF of its legs: a larger number increases the locomotion ability but at the same time reduces the feasibility of a working prototype, due to the complexity of the required actuation system.

The propulsion force must be larger enough to enlarge the tissue collapsed over the capsule's body. A value of force needed for locomotion has been estimated thanks to a simulation based on the theoretical model described below.

III. MODELING AND SIMULATED RESULTS

As introduced in the paragraph above, the design and development of an active legged platform for gastrointestinal operation requires deep knowledge in terms of legged locomotion efficiency, gait control, etc. For this reason, from the early stage of the research, authors developed in parallel experimental [7] and theoretical [8] platforms for guiding and optimizing the design phase and for deriving the most important locomotion parameters.

The capsule has been schematized in Fig. 1. Just as an example it possesses 8 legs, but the model is valid for **N**-legged devices.

Independent variables in the modeling are the relative coordinates of the tips, expressed by vectors $\mathbf{r}_i$, corresponding to on board actuation of the legs.

In modeling the legged capsule inside the GIT, the basic assumption which has been made is to consider the output motion of the capsule as a sequence of configurations characterized by static equilibrium (resultant force and moment equal to zero), thanks to the fact that in miniaturized systems having low speed, as in the case of the legged microcapsule, inertial forces become negligible with respect to contact interactions. Referring to Fig. 1, equations modeling the system are the following:

$$\begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix} = f_1(\vec{r}_i, x_c, y_c, z_c, \varphi_c, \theta_c, \psi_c) \quad i=1,..,N \qquad (1)$$

$$\vec{F}_i = f_2(x_1,\ldots,x_N, y_1,\ldots,y_N, z_1,\ldots,z_N) \quad \text{`` ``} \qquad (2)$$

$$\sum_{i=1}^{N} \vec{F}_i = 0 \qquad (3)$$

$$\sum_{i=1}^{N} \vec{F}_i \wedge \vec{r}_i = 0 \qquad (4)$$

f_1 is the known relation (composition of rigid motions) for obtaining the absolute position of each leg tip starting from its relative coordinates with respect to the capsule. f_2 is the experimental relation (found via *ex-vivo* experiments on GI tissue) for deriving the force due to the contact and due to two main phenomena: the bio-elasticity and the bio-tribology of the gut tissue. Equations (3) and (4) describe static equilibrium to translation and rotation. Unknown variables are the positions of leg tips (x_i , y_i , z_i), the coordinates of the capsule (x_c , y_c , z_c , φ_c, θ_c, ψ_c) and the forces F_i arising at the leg tips. Therefore the number of unknown scalars is equal to 6+6N, which is the same than the one of scalar equations. Leg tips configuration, described by vectors r_i, are input data, whose dependence on time makes the gait pattern.

For gut modeling, the selected approach is based on the schematization of an intestine segment as a tubular viscoelastic element with pure membrane strains and stresses. A geometrical description of the intestine tract has been performed by using Matlab$^{\text{TM}}$ software. The in-built function "convhulln", able to find the convex hull of a point set, has been adopted. Fig. 2 shows the modeling of an intestine tract

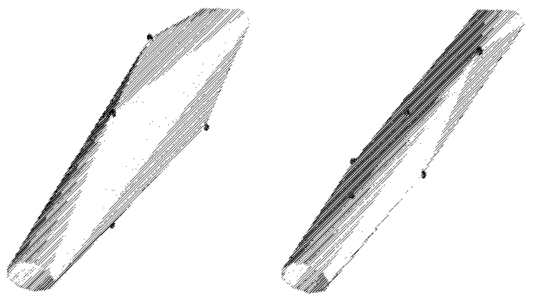

Fig. 2: The legged capsule deforming the gut tissue from the inside. Small markers indicate contact points between the device and the GI walls.

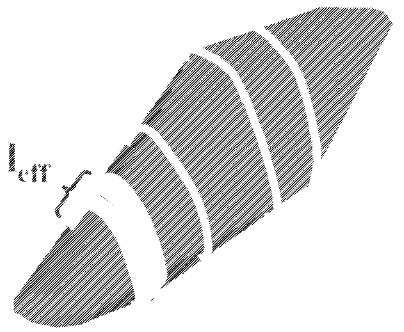

Fig. 3: The transversal size of the deformed gut is computed at each contact location and a discrete parameter model is adopted. The force applied by the tissue on the single leg tip is locally obtained with an equivalent force provided by a tract of tissue having width equal to l_{eff}.

deformed by an 8-legged capsule. Each leg is identified in the simulation with its tip (a point, external to the capsule, capable of moving along the three spatial directions). Frames have been extracted from a simulation generated for a gait pattern where all the legs move with an elliptic motion in forward direction. Small spheres represent leg tips, while arrows indicate those legs (front and back legs) generating motion force. Fig. 3 describes the methodology followed for obtaining individual forces on leg tips by the adoption of a discrete parameter model.

Inverse kinematics for the computation of the joint coordinates in the leg can be done for the optimal capsule design. Performances, such as power required for locomotion, energetic efficiency associated with gait patterns and capsule displacement, can be derived thanks to the knowledge of forces arising at each leg tip.

Starting form the modeling described above, two distinct movies are generated for the simulation: the one of the tissue being deformed by the capsule, and the one of the capsule itself moving its legs and propelling (i.e.: changing its position). These two graphical outputs have been merged using video editing software. In order to obtains exact synchronization, the same number of frames per second has been imposed, while for spatial registration the same location and viewpoint have been adopted both in the Matlab™ graphic interface and in the Pro/Engineer rendering environment.

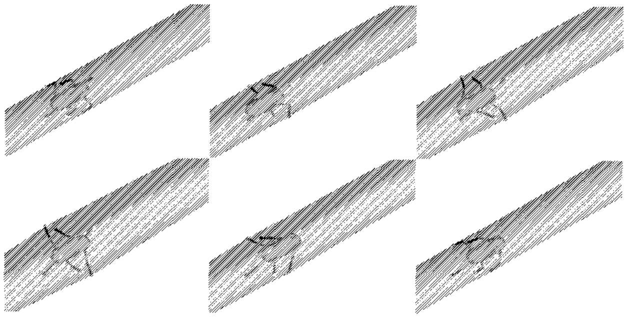

Fig. 4: Snapshots from a forward gait sequence where front and back legs move synchronously.

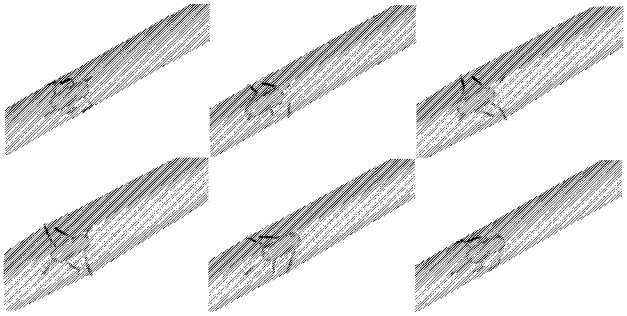

Fig. 5: Snapshots from a forward gait sequence where front and back legs move in alternate way.

In Fig 4 and Fig. 5 snapshots of typical movies on forward capsule motion are reported. In particular the two motions have been evaluated for two different gait patterns: the first one corresponds to front legs moving synchronously with rear legs, while in the second one alternate gait (i.e. 180° phase shift between front and rear legs) is applied.

These first models are an example of how it is possible to evaluate gait patterns effectiveness through simulation. In fact, in the first case the forward motion is much less than in the second, with the same needed energy.

IV. LEGGED PLATFORM AND PRELIMINARY TESTS

Preliminary legged platforms have been designed and fabricated by using Shape Memory Alloy (SMA) actuators for the leg operation [4], just to validate the legged principle. Afterwards, based on the experimental results and on the theoretical simulation, the authors realized that a larger force at the leg tip was necessary for obtaining a net propulsion (about 1 N rather than the 0.2 N generated by the SMA actuated legs).

A new capsule with an internal miniature motor able to activate 4 back flexible legs has been developed, as illustrated in Fig. 6.

The actuation system consists of a central screw (1) and four helicoidal gears (2) mounted on it; the four back legs (3)

Fig. 6: Gear motor endoscopic capsule: external view (left) and internal description (right)

are inserted in four pulleys (4) which are connected with the helicoidal gear: in this way when the gears rotate the legs rotate too. The screw is actuated by a commercial miniature motor (Micro DC Brushless motor - NAMIKI, Precision Jewel Co., Ltd) (5) whose diameter is 4 mm and whose length is 27 mm, including the gearbox, and a stall torque of 10.6 mNm. With this solution, the final diameter of the capsule is 12 mm and the final length is 40 mm, including a miniaturized CMOS camera with illumination.

Several advantages offered by this capsule with respect to the SMA-actuated one. First of all the external surface can be completely covered by a shell, because the miniature motor not requires cooling. Second, the capsule size is limited in comparison with the size of the SMA prototype used in the last test session;

Third, the propulsion developed by the single leg is 2-3 times larger than for the SMA leg the maximum force at the tip of the leg is about 1 N with a leg speed of about 1.5 cycle/min (with cycle we consider a whole open/close phase from 0° to 120° and vice versa). In addition the spanning angle of the legs is larger (140°) than the span reachable with the SMA actuators (110°-120°), more controllable, repeatable and reliable.

This capsule have been extensively tested *in vitro*, by using a dedicated set-up with freshly explanted pig intestine. We observed a net locomotion propulsion and a good efficiency of the back leg to open the normally collapsed intestine. In particular, in order to reduce the frontal friction during locomotion, we introduced a latex small balloon in the frontal part of the capsule (Fig. 7).

A set-back of the current device is the slipping effect at the end of each leg action cycle. In order to avoid this effect, which is currently the most important limitation of locomotion efficiency, a second, frontal pair of legs should be considered. These additional legs can counteract the unintended backwards motion of the capsule and could also avoid the use of the frontal latex balloon.

The main features of the locomotion capsule with miniature motor are the following:

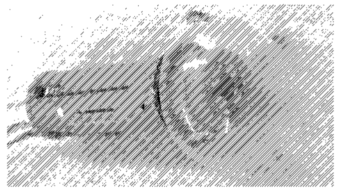

Fig. 7: Gear motor endoscopic capsule with frontal balloon.

- D=12 mm, L=38 mm
- Force of 1 N for each leg (theoretically)
- Power consumption: 290 mW
- Locomotion speed in vitro: 92 mm/min

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