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Miniaturized Robotic Devices for Endoluminal Diagnosis and Surgery: a Single-Module and a Multiple-Module Approach

A. Menciassi, *Member, IEEE*, P. Dario, *Fellow, IEEE*

Abstract— **This contribution presents the authors' activity in the field of miniaturized robots for surgical and diagnostic tasks with an endoluminal or a minimally invasive approach. Robotic capsules for diagnostic purposes in the gastrointestinal tract and endoluminal or transluminal robot concepts with bimanual abilities for surgical tasks will be presented, by highlighting the peculiarities of both approaches in terms of advantages, limitations and design challenges.**

I. Introduction

Surgical and diagnostic robots have been widely accepted in the last decade and contributed very much to the development and evolution of minimally invasive surgery techniques. The reason of this general acceptance can be recognized in the ability of robotics to improve surgical procedure accuracy, predictability and quality. Robots for orthopedic implantations or hand-held mechatronic tools for tremor compensation have improved very much the outcome of delicate surgical procedures, thus producing a standardization of surgical practice.

Nowadays there is a growing interest in adding robotic features also to simple and miniaturized surgical tools and to take advantage of robotic accuracy and high level performance also in endoscopy and minimally invasive interventions. Impressive surgical robots such as the Da Vinci robot could be soon accompanied by miniaturized *in vivo* and internal robots. In fact, concerning diagnosis, monitoring and basic therapeutic tasks (e.g. drug releasing) in the gastrointestinal (GI) tract, the trend of research is going from teleoperated master-slave manipulators to miniaturized endoluminal devices [1] and endoscopic capsules [2]. Commercial capsule endoscopes have generally no locomotive and therapeutic functions. Therefore, in order to improve controllability and precision of diagnosis, advanced endoscopic capsules have been studied, including legged capsules [3], pneumatically actuated endoluminal devices with inchworm-type locomotion [4], locomotive capsules driven by external magnetic fields [5], etc.

As regards surgical tasks, requiring a more advanced kinematics that cannot fit in a capsular device 2-3 cm^3 in size, endoluminal mobile robots for biopsy [6] have been demonstrated in the new surgical procedures called Natural Orifice Translumenal Endoscopic Surgery (NOTES) [7]. In this case, the surgical tools are inserted from a body's natural opening to approach the target organ without visible scars, and thus they are reconfigured or combined together for performing the surgical task. These devices are promising for the future advances of minimally invasive and endoluminal surgery, but the current development must face with major problems in terms of mechanism miniaturization and device power performance.

In Section II, some examples of endoscopic capsules for diagnosis will be introduced and discussed. Parallel approaches for developing miniaturized robots for visible scar-less surgery will be introduced in Section III. Finally, conclusions are reported in Section IV with a short discussion about barriers, limitations and problems related to the introduction of these novel technologies in the surgical practice.

II. Endoscopic Capsules for GI Diagnosis

Commercially available endoscopic capsules cannot be considered real robots: they are vision sensors provided with transmission abilities, but without any possibility to be controlled by the user, i.e. the endoscopist. Transforming a swallowable sensor in a robotic system with approximately the same size is a very challenging task. In fact, required forces and torques for dilatation of the intestinal tissues and for advancing in the GI tract are very high [8]: previous achievements of the authors in capsular endoscopy have demonstrated that each active degree of freedom added into a capsule requires approximately a power of 500 mW, in addition to smart and complicated internal mechanisms. This means that major problems arise in terms of battery duration and volume, with dramatic limitations for the integration of all the other diagnostic components (e.g. vision sensors, optics, telemetry, drug delivery modules, etc.) [9-10]. A large part of the mechanical power required for active locomotion in the GI tract is necessary for the organ distension. If organ distension can be achieved by liquid

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A. Menciassi is with the Scuola Superiore Sant'Anna, CRIM Lab, Pisa, ITALY (phone: +39 050 883418; fax: +39 050 883497; e-mail: arianna@sssup.it).

P. Dario is with the Scuola Superiore Sant'Anna, CRIM Lab, Pisa, ITALY (e-mail: dario@sssup.it).

ingestion, thus the power required for teleoperated exploration of the liquid filled organ (e.g. the stomach) is much more limited and miniaturized locomotion capsules can be developed without compromising the integration of additional diagnostic and therapeutic modules [11].

The problem of power requirement for obtaining both locomotion and organ distension is well illustrated in Fig. 1: the legged capsule has two degrees of freedom for moving two sets of legs and it needs an additional module for the battery, the diver and the telemetric chip. In fact, the high torques required for legged locomotion involve a power of approximately 600 mW and a motor total size that takes the entire space of a swallowable capsule.

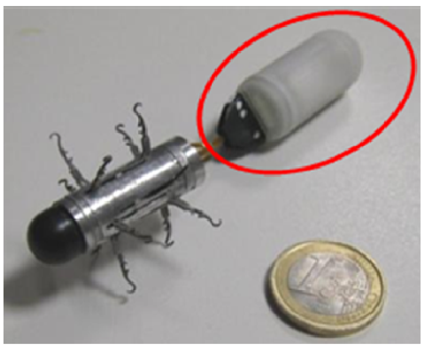

Fig. 1. Legged capsule with two set of 6 legs. Each leg set is actuated by one high torque miniaturized motor. The legs are shaped in order to increase the friction with the intestinal tissue. The tender module (in the red circle) hosts a battery pack and the motors driver. Without the tender, the capsule is wired, being the power consumption too high for an embedded battery pack.

On the other hand, in swimming locomotion, the torque and force requirements are less strict and in a swallowable volume there is room for all subsystems and functionalities: motors, battery, telemetry and imaging system, as reported in Fig. 2.

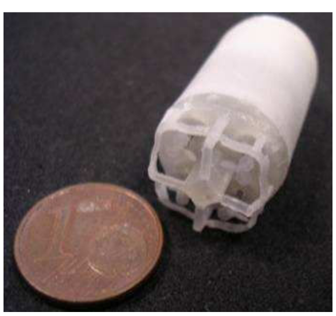

Fig. 2. Wireless swimming capsule with 4 propellers activated by 4 low torque miniaturized motors. Battery pack, motor drivers and telemetry chip are embedded in the capsule shell.

A compromise for achieving active locomotion by avoiding powering problems is combining external locomotion means with only one internal degree of freedom, thus allowing to modify the external profile of the endoscopic capsule and making easier the management of collapsed areas of the intestinal tract. While the internal locomotion mechanism can resemble the legged capsule mechanism, for the external locomotion propulsion we have developed a magnetic system exploiting an external large permanent magnet and one or more small internal permanent magnets. The external magnet is mounted on a robotic manipulator, for improving motion precision, and it is responsible for a rough drag and positioning of the capsule [12]. When facing with difficult areas, the internal locomotion mechanism can be activated, thus modifying the capsule external shape and helping to overcome bends and collapsed tissues.

This solution for capsule locomotion based on internal + external locomotion means (i.e. hybrid locomotion) has several advantages. First of all, there is more space free in the endoscopic capsule for hosting additional modules. For example, the hybrid locomotion capsule in Fig. 3 (right) is totally wireless, while the capsule in Fig. 1 needs the tender module for a complete integration of sub--modules. In addition, the typical abrupt gradients of magnetic fields can be tuned precisely with the help of high precision robotic arms (Fig. 3, left). Unpublished results by the authors have already demonstrated that robotic magnetic locomotion of endoscopic capsules is much better than manual displacement of the driving magnet in terms of precision and repeatability.

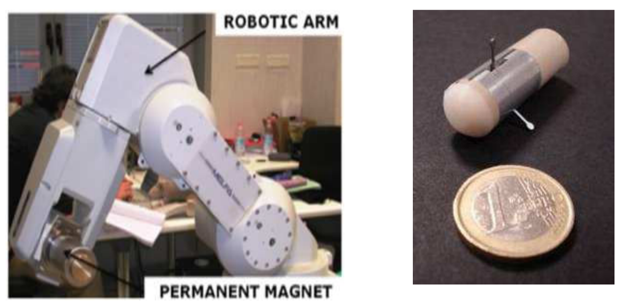

Fig. 3. Robotic manipulator for controlling the permanent magnet to be used for capsule motion (left). Hybrid capsule embedding a set of leg for shaping the external profile of the capsule and small permanent magnets, integrated in the white bottom section (right).

III. Endoscopic Robots for GI and Abdominal Surgery

As explained above, active locomotion in swallowable size poses important technical limitations if we cannot use external sources of power or external locomotion means.

Achieving the dexterity (e.g. 6 degrees of freedom), velocity (about 30°-360°/s) and force (between 1 N and 10 N) of typical surgical tasks required in endoscopic and laparoscopic capsule is unfeasible in a swallowable device.

A reconfigurable robotic system based on many capsule-like modules to be assembled inside the hollow organs of the GI tract is proposed [13] to overcome the intrinsic limitations of single-capsule approach. In this system, tiny robotic components are ingested and assembled by themselves to configure a structure in the stomach (or in the abdomen, by performing an incision in the stomach wall) with the objective to perform precise interventions [14]. The multi-capsule scheme facilitates the delivery of more components inside the body and the robotic reconfiguration allows the precise positioning of the therapeutic tools which can cooperate to perform complicated surgical tasks.

Fig. 4 shows the design of one structural module with 2 degrees of freedom (±90° of bending and 360° of rotation) and a picture of a preliminary robot prototype combining 16 modules like this together. Each active module contains a Li-Po battery (20 mAh, LP2-FR, Plantraco Ltd., Canada), two brushless DC motors 4 mm in diameter and 17.4 mm in length (SBL04-0829PG337, Namiki Precision Jewel Co. Ltd., Japan) and a custom-made motor control board for wireless control.

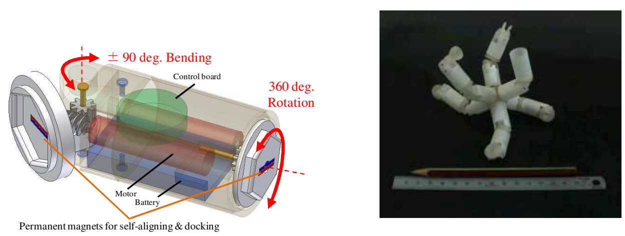

Fig. 4. Mobile module for reconfigurable endoluminal surgical robots with 2 degrees of freedom, battery, control, wireless communication and dedicated attachment structures (left). Combination of 12 different module for building up a surgical robot with high dexterity and integrating a biopsy tool (right).

In order to improve the stability of the internal robotic system, the accuracy of the surgical tasks, and an adequate powering, a tethered configuration has been also considered. The esophagus is a natural orifice of the human body: it can be used as an access port to the stomach and also to the abdominal cavity – by perforating the stomach wall in a NOTES approach . Consequently, we could devise an endoluminal procedure where the robot modules – pre-linked, if necessary – are introduced through the esophagus to the stomach or to the abdomen [15-16]. There, the modules can be configured in a bimanual platform by using external permanent magnets to improve stability [17], while a panoramic camera at the bottom of the access port visualizes all the operative area. A sketch of this concept is reported in Fig. 5.

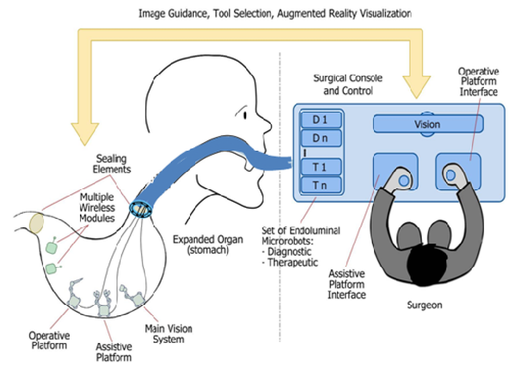

Fig. 5. Sketch of an endoluminal tethered surgical robot (operating in the stomach, in this concept) introduced by the natural access port of the esophagus (from the ARAKNES project [15]).

In order to improve the stability of the internal robotic system, the accuracy of the surgical tasks, and to provide an adequate powering, an endoluminal robot with both some internal actuated degrees of freedom and some external actuated degrees of freedom (for high torque and high speed) is under consideration in the authors' group.

IV. Conclusions

This paper presented several miniaturized robotic solutions for diagnosis and intervention in the GI tract or in the abdominal cavity, by highlighting the specific requirements in terms of working area, necessary power, and device size. For diagnostic tasks in the GI tract, a single capsule approach is presented, where several solutions can be feasible: wireless or wired devices with on-board actuators for active locomotion; swimming capsules for exploration of organs filled with liquid; hybrid capsules moved thanks to the interaction of external and internal permanent magnets in addition to one internal degree of freedom.

While active capsule prototypes for diagnosis are already at a good level of engineering and testing, bimanual surgical tasks for abdominal surgery require specific efforts. In this framework, a multiple-module approach has been investigated: a reconfigurable surgical system based on multiple assembling capsules is at the proof of concept level, and some devised solutions for building up a bimanual platform for endo- and trans-luminal surgery are under development.

The future in the field of endoluminal and transluminal devices is growing bright. From the technical standpoint, endoscopic capsules with some action functionalities - in addition to the always present imaging functionality – are becoming a reality. There are many research efforts in hybrid locomotion techniques relying on external magnetic fields. In fact, although many different strategies can be identified for capsule controlled propulsion, magnetic actuation is receiving a great attention in these last years and it is rapidly producing innovative concepts. It is due to observe that in different medical fields (e.g. catheter guided therapy for heart diseases and vascular apparatus) commercial systems exist guiding catheters with the help of a remote magnetic navigation system (http://www.stereotaxis.com/). The Stereotaxis system utilizes two permanent magnets mounted on articulating or pivoting arms that are enclosed within a stationary housing, with one magnet on either side of the patient table, in the catheterism laboratory. Anyhow, important challenges related to magnetic field tuning, controllability and achievable forces have still to be approached and many open issues still remain.

As regards endoluminal surgical system, major technical problems are still to be solved and they are related to the stability of the internal surgical platform, to the transmission of mechanical power from external actuators, or - alternatively - to the generation of high torque at high speed by smart actuators integrated into the internal platform. Several novel concepts are emerging, but the physical limitations posed by the surgical requirements (large forces up to 5-10 N, 6 degrees of freedom for each surgical arms, real time controllability of remote actuators) are severe and many barriers still exist. In this scenario, the most promising solutions will probably emerge from a combination of different accesses to the human body and from a smart integration between on board actuators and external driving units.

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