MEDICAL MICRO-ROBOTICS

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Abstract *- The rapid growth of minimally invasive surgery and therapy (MIS and MIT, respectively) has generated the need for smaller and smaller medical tools with enhanced diagnostic capabilities and high dexterity. The development of micro-machines require an approach rather different from the one followed in traditional machine design; if the field of application of micro-machines is the medical one, the design approach is even more peculiar.*

In this paper the authors present some concepts useful to model and design a micro-machine. The concepts are derived by considering the case of scaling down the size of a submarine for possible navigation in the circulatory system. Then, we discuss the design of some micro-machines for general medical applications, the main problems to be addressed and the different technologies exploitable to fabricate them. As a case study, we present the development and some preliminary experiments on a of a micro-endoscope for the gastrointestinal tract.

1. INTRODUCTION

Table-top factories which assemble mini-devices with high accuracy and at low cost [1], micro- and nano-robots which "swim" in the human body to detect and treat diseases [2], micro-motors which exploit as working principle the DNA behaviour may be soon not just the dream of researchers, but real and working "micro- and nano-machines".

A micro-machine is a machine with size ranging between 1 mm and 1 μm, designed and fabricated according to the methods and technologies of micro-engineering. As a mechatronic system, a micro-machine integrates harmonically mechanisms, actuators, sensors, embedded control, power supply and user interface in a smart, compact and small device. But the design rules, the simulation tools and the fabrication technologies of micro-machines are different from those used with normal-size machines. One cannot develop effective micro-machines simply by "scaling down" the standard rules, tools and technologies of traditional mechanical engineering.

The criteria of mechanical efficiency for micro-machines are very peculiar: friction phenomena are considerable in the micro-world; flexure joints often must substitute rotary joints; flat structures generally scale better than 3-dimensional structures; dynamic behaviour extends to higher frequencies.

Also simulating a micro-machine is not trivial: thermo-fluidic effects change their relative weight and can unexpectedly modify the behaviour of micro-sized machines; to optimise functionality and efficiency the micro-engineer could be inspired by small biological creatures like insects and bacteria.

Finally, micro-fabrication and assembly technologies must be developed in order to obtain 3D micro mechanical components. The choice of the enabling technologies - often derived from the combination of precision 3D machining, 2D microelectronics technologies, patterning of bio-elements and robot-assisted assembly - must follow, but also proactively drive, the design and simulation phases.

This paper aims to provide an overview of some concepts and rules which allow to design and fabricate a micro-machine. These aspects are presented in Section 2. One of the emerging medical sectors where these rules are important is endoscopy, which is analysed in Section 3. As a case study, endoscopy in the gastrointestinal tract as performed by smart mobile micro-machines is presented in Section 4. Finally, some design steps and experimental results are discussed in Section 5, with reference to the authors' experience.

2. GENERAL ISSUES ON THE DESIGN OF MICRO-MACHINES: THE MICRO-SUBMARINE

In order to make the analysis of the design and fabrication of a micro machine more concrete, we have selected to investigate the problem of designing f a micro-submarine.

Many popular science fiction (SF) writers have been captured by the dream of navigating inside the human body to explore that unknown but intriguing world. At present, researches are conducted in different laboratories, including the authors' one, to develop devices able to move inside the living body: the SF edge is finally approaching the reality domain.

The concept of an autonomous submarine able to propel itself in the human body is closer and closer to real application, especially in the medical field (Figure 1).

***Figure 1**. From the left: a micromachine for pipe inspection (Toshiba); a pill size camera for gastrointestinal diagnosis (Given Imaging Ltd); a prototype of microrobot for vessel inspection, fabricated by stereolithography.*

For the sake of analysis, we consider the design and fabrication a miniaturised submarine whose diameter is 500μm. In particular we wish to scale by a factor N=5000 the model of a real size ancient submarine of Figure 2 (on the left) in a miniaturised submarine as illustrated on the right (not in scale).

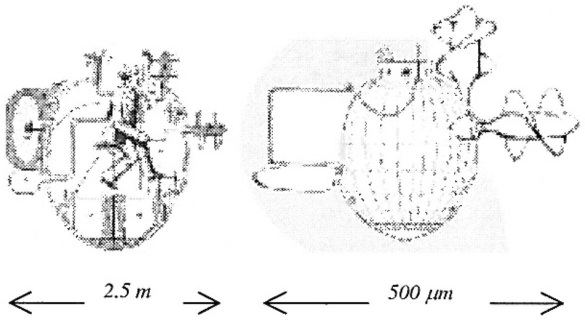


***Figure 2**. The "Turtle" man-powered submarine by D. Bushnell, 1776. Left: original proportions. Right: effects of scaling down.*

The problems to be addressed are many. Some of them are listed here:

- would the man in the submarine notice any difference in the surrounding liquid environment as his size and the size of the submarine become smaller and smaller?
- how would the shape of propellers change?
- How should be dimensioned the mechanisms?
- How would propulsion efficiency scale and what kind of energy storing device could be used if we substitute the human "motor" with an electrical one?

The answer to all these questions can be given in terms of classical physics, because all the traditional laws of Newtonian mechanics apply. The only fundamental change that occurs is in the relative magnitude of acting forces. As is well known, the Reynolds number, Re, is a factor that plays a fundamental role in almost all the fields of fluid mechanics. Re is proportional to the ratio between inertial and viscous forces acting on a body surrounded by a fluid. The higher is the value of Re, the bigger are the inertial forces as compared to the viscous ones. In the case of the micro-submarine, the Reynolds number can be calculated as the submarine speed (v) multiplied by the submarine diameters (D) and divided by the kinematics viscosity of the fluid (ν). Since time and the physical properties of the fluid do not change, if we reduce the dimensions of the submarine, the Reynolds number perceived by the tiny passenger is about N^2 times the value calculated by a standard observer. In other words, the tiny passenger *feels* the surrounding liquid as extremely dense and viscous. The propellers, effective in the macro world, would be useless for locomotion in the micro world; the passenger would prefer to have very large propellers, similar to rotating paddles. From an engineering point of view, this consideration can be interpreted as follows. We define the efficiency of a propeller based locomotion system as:

$$\eta = \frac{\mathrm{v} \cdot \text{advancement force}}{\text{motor supplied power}} \cong \text{viscosity} \cdot \frac{\mathrm{D} \cdot \mathrm{v}^2}{\text{torque} \cdot \text{angular speed}} \qquad (1)$$

If we suppose that the angular speed is kept unchanged, we must evaluate the scaling law for the required torque. The exact solution is very complex. Nevertheless, we can estimate the order of magnitude of the torque as:

$$\text{torque} \cong (\text{density})\,(\text{angular speed})^2 \cdot \cdot\,(\text{propeller area}) \cdot D^3 \qquad (2)$$

From (1) and (2) it descends that the efficiency of propellers decays, quite severely, as N^2. To save efficiency, the size of the propeller should be reduced less than the size of the submarine body. For hydrostatic reasons, directional and balancing organs should be also relatively enlarged, as shown in Figure 2 (right). From a structural point of view, large propellers require a driver shaft of adequate diameter. Since the structural properties of materials are not affected by scaling, it is easy to find out that the diameter of the propeller shaft should scale only as $N^{1/3}$, thus resulting in an unexpectedly large diameter shaft.

2.1 Considerations on energy

In the same way, we have to take into consideration some issues on energy. A man who in average produced 200 W powered the original submarine.

If the conventional size propellers had an efficiency of 0.9 and an average speed of 0.5 m/s, the miniaturised submarine would have an almost negligible propeller efficiency of $3.5\ 10^{-8}$, it should move at 100 μm/sec and it should absorb 1.3 μW.

The energy inefficiency of the propulsion system affects the required power density: by supposing that the *total* volume of the micro machine is available for energy storing, the required power density would be about 20 $\mu W/mm^3$, a value quite high even if compared to current high efficient fuel cells.

2.2 Structural considerations

From a structural point of view, the miniaturization of a mechanical device has to take into account the lack of geometrical similitude with the macroscopic world. In fact the thickness of the submarine wall has to withstand a lower pressure if the working environment scales together with the submarine size. More precisely, the dimension coefficient C_S (e.g. the ratio between the wall thickness and the linear dimension of the submarine) scales linearly. Simple relations on force balance show that:

$$C_S = K \cdot \frac{\rho g}{\sigma_{max}} \cdot D \qquad (3)$$

where K is a dimensionless constant, ρ is the density of the fluid in which the submarine navigates, g is gravity, σ_{max} is the maximum stress in the wall material.

Therefore, according to equation (3), a 500 μm diameter submarine could have a C_S ratio extremely small, about 0.02 % the value of C_S in the macro world. This would result in a tiny, “insect-like” shell for the miniature submarine.

3. MICRO-MACHINES FOR ENDOSCOPY

Minimally Invasive Therapy (MIT) and Minimally Invasive Surgery (MIS) seek to provide to the patient, the medical doctor and the health care system many advantages in terms of better quality of care, shorter hospitalisation and reduction of pain and medical complications. MIT and MIS techniques are well established in some medical fields, e.g. laparoscopy and arthroscopy, but new fields of application are currently investigated and considered as very promising, such as local treatment of tumors and even single cell surgery [3].

Limited access to the target organ and reduced amount of information (visual and tactile) available to the surgeon for planning and performing the operation are serious limitations of MIT and MIS. These limitations can be addressed through micro engineering design, which allows to increase the performance of miniature instrumentation and to enhance feedback to the surgeon by means of miniaturised sensors and actuators incorporated in the endoscopic tool.

There are some examples of such “smart” miniature endoscopic tools. Active catheters with multiple tactile sensors mounted at the tip have been designed and fabricated by Olympus Optical Co., Tokyo, Japan. A typical catheter incorporates two shape memory alloy (SMA) wire bending actuators.

The tactile sensors are fabricated monolithically on flexible film using thinned integrated circuits. The tactile system in the catheter includes three tactile sensing elements, one passive sensor for temperature compensation, and aluminium connection wires.

An instrumented micro-catheter, less than 2 mm in diameter, with on-board integrated CMOS interface circuits for communication and control has been developed at Tohoku University, Japan. The actuation is SMA-based: each SMA actuator is driven individually, thus allowing selectable bending of the catheter. A view of the system is shown in Figure 3.

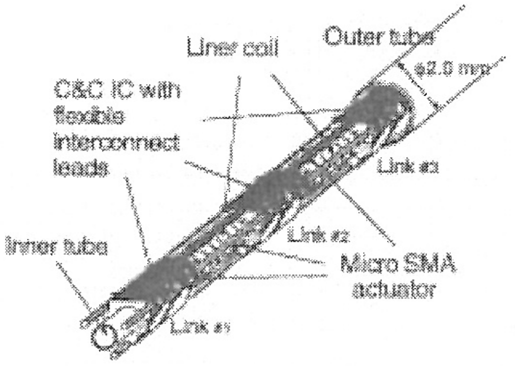


***Figure 3.** Active microcatheter with integrated circuits.*

4. MICRO-ENDOSCOPES FOR THE ANALYSIS OF THE GASTROINTESTINAL TRACT

Presently, various types of rigid and flexible endoscopes are used to inspect and to perform therapeutic procedures in different parts of the gastrointestinal (GI) tract. Due to the working characteristics of conventional endoscopes, most GI endoscopy procedures are unpleasant for the patient, and are technically difficult and require long training periods for the endoscopist. Furthermore, even with the latest wired endoscopes, large part of the small intestine still remains unreachable. Studies have shown that most GI ailments can be cured if detected in the early stages, which means that mass screening of the population for GI ailments would save lives.

In order to render mass screening possible, we are developing devices for semi-autonomous or autonomous locomotion in the GI tract. These devices will be introduced into the anus or mouth and will function as transportation means to carry the vision system and other endoscopic tools to the area of interest in the GI tract, ideally without causing discomfort to the patient.

Pill-size mini-cameras could perform effective and reliable diagnosis if they could detect abnormalities in the *entire* gastrointestinal tract by inspecting the *entire* gastrointestinal wall. As demonstrated by the endoscopic micro capsule developed by Given Imaging Ltd [4] relying only on normal peristalsis, sufficiently clear images of the small intestine, pylorus and duodenum, can be obtained. These organs have small lumen and diameter, similar to that of the capsule. The possibility to stop, move forward and backward, and rotate is of paramount importance for the on-board micro camera to look at every place of the gastrointestinal wall. This ability would result in more accurate and reliable diagnosis and, in future applications, even in minimally invasive biopsy and localized therapy (e.g. drug-delivery) .

4.1 Novel locomotion solutions for the GI tract

A few different locomotion mechanisms for semi-autonomous endoscopes have been proposed by various researchers [5-7]. We are approaching the problem of locomotion by exploiting an inchworm device which is particularly suited to unstructured or even hostile environments where wheels and tracks fail [8].

An inchworm device is made up of basically two types of actuators: the *clamper* and the *extensor*. The clamper is used to adhere or clamp the device securely onto the "terrain" while the extensor brings about a positive displacement (stroke). The simplest inchworm device consists of two clampers at its ends and one extensor at its mid section. Figure 4 shows the gait sequence in which this device propels itself forward.

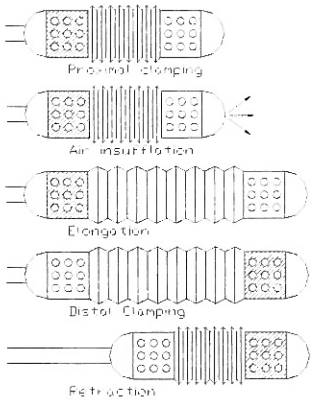


Figure 4. *Schematic diagram illustrating the sequence of the inchworm type locomotion concept. The shaded area on the distal and proximal clamping actuators indicates the active clamping states.*

The sequence begins with the proximal clamper actuated. With a secure grip on the GI tract, the extensor is activated to propel the distal clamper forward. At this stage, air can be introduced to inflate the GI tract, which is normally collapsed. When the extensor is fully elongated, the distal clamper is activated to grip onto the intestinal wall. The proximal clamper can then be deactivated to release its grip on the GI tract. This is followed by the retraction of the extensor to pull the proximal clamper forward. The cycle then repeats itself. Each cycle results in a net forward displacement, which is the stroke of the inchworm. Primarily, the stroke is the difference in length of the extensor in its elongated and retracted states.

4.2 Efficiency of the inchworm locomotion

Theoretically, the inchworm device should advance a distance equal to its stroke after each cycle of the locomotive sequence. However, this is not true in a real scenario. Losses could result due to factors like slippage, difficult bends and collapsible terrain. As such, we define *inchworm locomotion efficiency* (η) as the ratio between the real advancement and the theoretical one. The same efficiency can also be expressed as the ratio of real average locomotion speed and the expected one. The inchworm's locomotion can be broken into 3 distinct features: elongation, retraction and clamping. The individual efficiency of each of these mechanisms contributes to the overall efficiency (η) of the locomotion system. The overall efficiency can be represented by:

$$\eta = \eta_e \eta_r \eta_c$$

where η_e, η_r and η_c are the efficiencies of the elongation, retraction and clamping mechanisms respectively. Since η is directly proportional to each component, it is important to maintain high individual efficiencies for effective locomotion. It is also critical to fully understand the "terrain" of the locomotive device before an in-depth study of the efficiency can be performed.

In our application, the "terrain" is the human GI tract. Anyway, whatever the environment, no locomotion task can be performed without a qualitative and quantitative knowledge of the relevant features of the surfaces on which the machine will move. This knowledge must be acquired at two distinct and equally important levels. Referring to the inchworm device for GI tract, the first level refers to the mechanical viscoelastic behaviour of the tissues (i.e. displacements of the tissues once a force is applied), while the second refers to the bio-tribological properties of the surfaces, necessary to evaluate the frictional forces which can be exerted to perform locomotion. Then, it is essential to estimate the maximum forces which can be exerted without inflicting any damage to the tissues. For this aim, it is important to point out which is the most critical damaging cause and which are the limitations to the generated forces. Medical evidence shows that the maximum value of forces is determined at the threshold at which the integrity of the *vascular system* is disrupted.

As a general consideration, we can say that preliminary *in-vivo* and *in-vitro* tests demonstrate that clamping efficiency is the most critical parameter: if the tissue does not adhere to the device, a slippage condition appears and no locomotion is feasible.

For this reason, our efforts have been particularly devoted to develop effective clamper mechanisms.

5. PROTOTYPES FOR LOCOMOTION IN THE GI TRACT

5.1 Clamping system based on suction

A few prototypes - constituted by a bellow for elongation/retraction and by two clampers with holes for sucking the tissue - have been built in our laboratory. A typical version of inchworm device has the simple configuration illustrated in Figure 5.

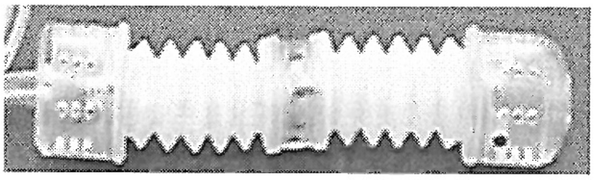


Figure 5. *Inchworm device with clampers based on pneumatic suction.*

These prototypes consist of basically two clamping actuators: proximal and distal. A flexible central rubber bellow acts as the extension actuator. The flexibility of the extension actuator enables the device to passively conform to acute bends in the colon. The diameter of the device ranges from 18 mm to 22 mm. Flexible air tubings exit from the proximal end of the mini-robot and are connected to an external pneumatic distributor. A computer is devoted to the activation of the solenoid pneumatic valves. The operator controls the movement of the mini-robot via a Human Machine Interface (HMI). The mini-robot can start, stop and increase or decrease its speed. Other parameters like air pressures to different actuators and the ability to insufflate air with controlled duration can also be adjusted from the HMI.

Extensive in vitro experiments on restructured pig's colon and a few in vivo experiments on anaesthetised pigs (who recovered fully after the experiments) were performed [9].

The following lessons were learned from these experiments:

- pneumatic clamping does not provide high enough efficiency because slippage occurs between hole surfaces and intestine wall (low clamping efficiency);
- the small holes used for suction are easily obstructed by debris during locomotion in the colon.

5.2 From suction clampers to mechanical clampers

In order to improve the locomotion efficiency, the most important point is the improvement of the clamping efficiency. The clamping mechanism was re-designed as illustrated in Figure 6.

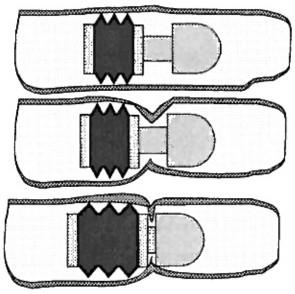


Figure 6. *(Description from the top to the bottom): The clamping mechanism is placed into the GI tract with its 'jaws' opened; a vacuum is introduced to cause the surrounding tissue to collapse into the 'jaws' of the clamp; the jaws of the clamp close to grasp onto the tissue.*

Due to the almost negligible coefficient of friction of the GI tract, insufficient traction forces are generated by simple suction. Moreover, undesirable lesions appear when the vacuum pressure is increased beyond a certain value. However, a notable occurrence is that with the introduction of a vacuum, tubular sections of the GI tract (colon, small intestine etc) would collapse around any hard object that is in the vicinity of the suction supply. In doing so, the GI tract would take the shape of the hard object, filling any gaps, holes or troughs in the process. To take advantage of this situation, instead of using the vacuum to attain traction forces, it could be used to cause the tissue to fall into the 'jaws' of a mechanical clamp (e.g. grippers, pincers, forceps). Having a prominent hold on the tissue, the 'jaws' of the clamp can easily close in for a positive grasp.

The typical prototype with central bellow for elongation and retraction and "suction + mechanical" clampers is illustrated in Figure 7.

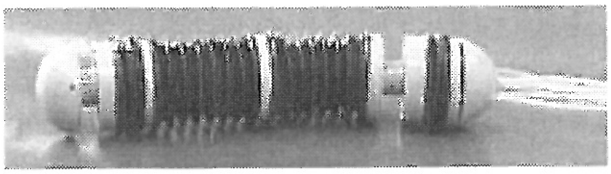


Figure 7. Prototype with mechanical clampers

It measures 24 mm in diameter and has lengths of 115 mm and 195 mm when retracted and elongated respectively. A flexible rubber bellow acts as the extensor which gives the device a stroke of 80 mm when extended. Rubber bellows are used to open and close the clamp jaws while a hole of 2 mm diameter situated in between the jaws is responsible for suction and insufflation of air. Flexible air tubings exit from proximal end of the device to form the 'tail' of the inchworm device. These are connected to an external pneumatic distributor. A computer controls the activation of solenoid valves which are responsible for driving the extensor and clampers according to a specified gait sequence.

5.2.1 In vitro experimental tests

In vitro experiments were carried out by exploiting a "home-made" simulator made of polystyrene. This artificial path was patterned according to the indications of medical doctors in order to reproduce a realistic 3-dimensional structure of the human colon (Figure 8).

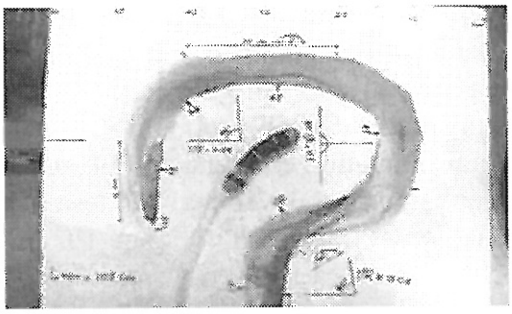
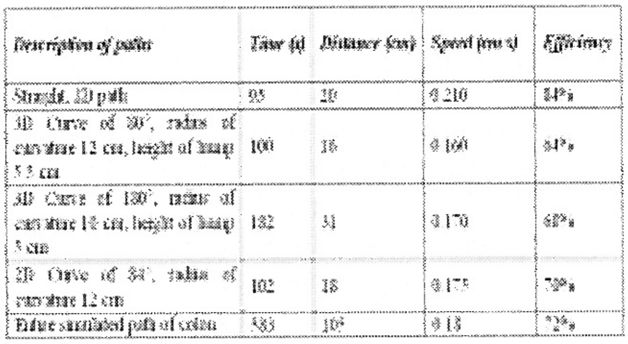


Figure 8. 3D colon simulator.

The overall size of the simulator was 60 cm x 90 cm x 20 cm and it included 60 cm of straight path and 105 cm of realistic "colon-like" curved paths. A pig's colon of length 150 cm was placed in the test bench and constrained at both its ends. Before inserting the prototype in the colon, all parameters were measured and optimized; the characteristics of the device's locomotion were as follows:

Stroke length: 8 cm
Time of 1 cycle of gait sequence: 32 s
Theoretical speed: 0.25 cm/s

The device was inserted in the colon and its performance was recorded both for the entire path and for each colonic tract (bend or straight path). Table 1 summarizes the experimental results.



Description of paths	*Time (s)*	*Distance (cm)*	*Speed (cm/s)*	*Efficiency*
Straight, 1D path	95	20	0.210	84%
3D Curve of 90°, radius of curvature 13 cm, height of loop 5.5 cm	100	16	0.160	64%
3D Curve of 180°, radius of curvature 18 cm, height of loop 5 cm	182	31	0.170	68%
2D Curve of 84°, radius of curvature 12 cm	102	18	0.175	70%
Entire simulated path of colon	583	105	0.18	72%

***Table 1.** Summary of in vitro test results.*

5.2.2 In vivo experimental tests

An *in vivo* experiment was carried out on a 35 kg male pig under general anaesthesia. The experiment was performed in an authorized laboratory, with the assistance and collaboration of a specially trained medical team in accordance to all the ethical considerations and the regulatory issues related to animal experiments. Prior to the experiment, the pig's bowels were properly prepared for colonoscopy. A colonoscopy procedure using a conventional colonoscope was first performed by a skilled endoscopist to inspect the terrain of the colon. 2 bends in the colonic tract were revealed during the inspection. The first, a gentle bend, was situated about 30 cm from the anus while the second, an acute kink, was situated about 50 cm from the anus.

After the withdrawal of the colonoscope, the prototype was introduced manually about 10 cm into the pig's anus. Upon activation of the gait sequence, the inchworm device propelled itself a distance of 40 cm into the colon with an estimated speed of 0.19 cm/s. After which, its speed decreases and the device was observed to remain stationary 55 cm from the anus. The gait sequence was stopped and the device was retrieved by manually pulling its 'tail'.

A second inspection with the conventional colonoscope revealed reddish clamping marks on the colonic walls. These were caused by the clampers as the device inched its way into the colon. According to the endoscopist, these marks were similar to those that appear occasionally during colonoscopy when the scope stretches the colonic walls excessively [10]. These marks normally heal within a few days. From the positions of the clamp marks, it is evident that the device surpassed the first gentle bend without much difficulty. The last clamp mark was situated a few centimeters after the second, more acute bend. This showed that the distal head of the device conformed and surpassed the second bend, thus propelling itself for the entire part of the GI tract necessary for a rectum-sigmoidoscopy diagnosis. In terms of efficiency, since the theoretical speed can be calculated to be 0.25 cm/s, the locomotion efficiency of the device was 76% along the straight portion of the colon; then it decreased to zero during the navigation of the second curve. The prototype has demonstrated high elongation and clamping efficiencies, and showed its ability to traverse pass the rectum, sigmoid and descending colon. The major drawback is its low retraction efficiency, which ultimately affects the overall locomotion efficiency.

6. FROM THE TESTS TO A NEW CONCEPT OF LOCOMOTION

On the basis of the experimental tests, a different configuration of locomotion device based on sliding clampers (which should be more effective in overcoming the bends) has been conceived and it is currently under development. Figure 9 shows a first prototype of this type of device.

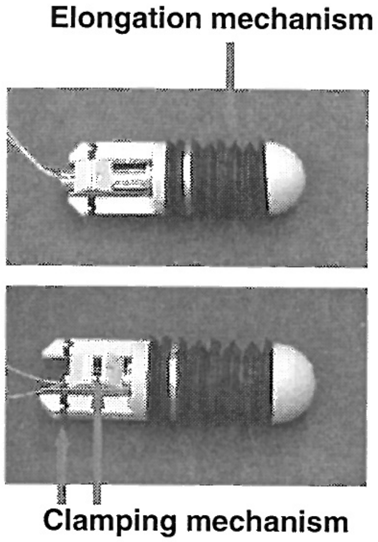


Figure 9. *Picture of the last prototype.*

The first clamper is located in between the second clamper. In the retraction phase, the linear actuator causes the first clamper to shift to the left, outside the enclosure of the second clamper. At this phase, the clamping surface of the first clamper is proximal with respect to the second one. The opposite happens in the elongated phase. The extensor extends to cause the first clamper to shift into the enclosure of the second clamper, resulting in the clamping surface of the first clamper being distal with respect to the second one. A repetitive sequence of these 2 phases would ensure that the clampers always grasp the tissue distal to its predecessor, thus eliminating the "bends problem."

Several miniaturized versions of the same concept are being developed and tested in our laboratory, as illustrated in Figure 10.

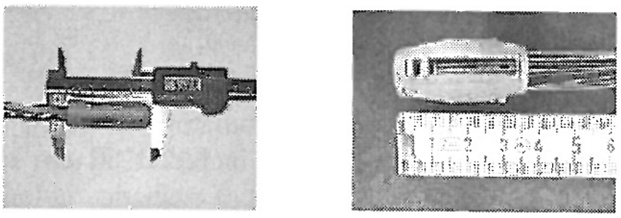


Figure 10. *New versions of locomotion prototypes based on sliding clampers.*

7. CONCLUSIONS

In this paper the authors presented some issues related to the modeling, design and fabrication of miniature and micro-machines.
The main problems encountered in the development of micro-machines for medical applications are illustrated by referring to a concrete case: the development of a semiautonomous robot for minimally invasive endoscopy in the GI tract.
Some design concepts have been presented and experimental tests have been discussed.

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