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ROBOTS IN MEDICINE: A SURVEY OF IN-BODY NURSING AIDS

INTRODUCTORY OVERVIEW AND CONCEPT DESIGN HINTS.

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SUMMARY.

Robots in medicine deserve enhanced attention, being a field where their instrumental aids enable exacting options. The availability of oriented effectors, capable to get into the human body with no or negligible impact, is challenge, evolving while micro-mechanics aims at nano-technology. The survey addresses sets of known achievements, singling out noteworthy autonomous in-body devices, either co-robotic surgical aids, in view of recognising shared benefits or hindrances, to explore how to conceive effective tools, tailored to answer given demands, while remaining within established technologies. Up now, indeed, the men' activity seems too much to move along anthropomorphic tracks and surgeons, typically, confront themselves with operation theatres at hands and eyes reach. This will not be the case with miniaturised equipment. Innovative answers with instrumental robotics look after duty-driven set-ups, optimally adapted to wholly assessed tasks; this will modify the interfaced surroundings, at least, due to quite different scale factors and accuracy reliability. Thereafter, robots in medicine are most likely a turn of accepted practices, centred on actual duty sequences and leaving aside solutions up-now preferred, since based on human testimonial evidence. This presentation provides a survey of current developments, in the spirit of focusing the trends toward the said turn.

1. INTRODUCTION.

Robots in medicine are recent entry, beginning as generic instrumental aids and aiming at specialised duties once technology sophistication enables effective settings. Several classifications are used, mainly, dressing a taxonomy by means of the expected accomplishments:

- patients and disabled aid: bed automation, walking assistants, delivery servants, etc.;
- laboratory support: clinical testers, radiation therapies assistants, etc.;
- soundness care: pace-makers, health-monitors, drugs dosing up suppliers, etc.;
- surgery help: surgeon's servants, remote effectors, autonomous actors; etc..

Moreover, roughly speaking, the example taxonomy distinguishes extra-corporeal fixtures, mainly derived out of conventional technologies, from *in-body* active devices, generally requiring invasive actions, thus, critically dependent on micro-mechanics and nano-technologies.

With focus on surgery robots, four kinds of tasks are, generally, considered:

- organ inspection: cerebral probing, laparoscopic monitoring, etc.;
- organ nursing or repair: internal anastomosis, obstruction relief, etc.;
- organ removal: cysts excision, splenectomy, lymph node dissection, etc.
- (artificial) organ implant: prosthesis insertion, etc. .

Traditional surgery moves with a wide incision on patient body to assure proper sight and to allow surgeon hands to reach the operating place. Besides anaesthesia effects, patient's pain and recovery heavily depend on the dissection size and tortuousness and on the excision width and depth. Of course, surgeon ability is relevant option, but damage cannot be lowered out of human operation scales. Surgery robotics, therefore, will establish a divide among today and tomorrow options.

Minimal invasive approaches will develop, by timely acknowledging the alternative option to transfer sight, touch and handling tasks to miniaturised effectors (as compared with human world). Completely new care protocols will affect brain injuries or diseases. Improved treatment will, also, establish for abdomen operations. Laparoscopy is today challenging prospect: surgical operations are remotely supervised and guided, through computer-control, by coupled robotic arms. The arms tips, carrying vision or surgical tools, are inserted into the patient body by small openings and along minimal impact paths. In the abdomen, carbon dioxide is pumped in, to create viewing and working room; one or more small cameras provide eye feedback to the surgeon; hectics and force data might, as well, be generated. Similar equipment is used for cardio-surgery, with relevant benefits in avoiding thoractomy and related chest staving in.

The analysis of presently conceived in-body robots provides reference description of current problems and hints about worthy innovations to extend effectiveness and to lower invasiveness. Next section is, thus, devoted to an explanatory survey. The final section addresses an example set-up to summarise peculiarities of the domain technologies and to prospect concluding comments on next generation medical robots.

2. SURVEY OF ROBOTIC IN-BODY EQUIPMENT.

The in-body active devices open innovative trends, distinguishing: - for duty bent, probes (inspection, drainage, drug-release, etc.) and effectors (dissection, legation knitting, etc.); - for invasiveness, insertion through natural ducts or after artificial incisions. Endoscopy is increasingly available technique; compared to earlier means, main advantages are painstaking (strictly localised details) and magnification (allotted power supply). Moving from endoscopic probes, extensions are sought by analogies or by functional bents, aiming at considerably broadening the task domain.

Within the recalled framework, several review criteria could be followed; since technical trends, rather than exhaustive classifications, are addressed, invasiveness figures are special reference. The survey, thus, moves from current concepts typically accounted for to achieve high conservativeness, then provides a few example devices for explanatory purposes, addressing: (externally handed) sounds, (travelling) worms and (floating) pills. In the final paragraph, hints on prototypal studies follow, to widen the application field of in-body robotics.

2.1. *Trends of in-body medical robots*.

Robot aids originate from active probes, actuated catheters or instrumented endoscopes, adding task-planning capability and functional autonomy. One should distinguish:

- the insertion path: through existing orifices/ducts or by means of carrying trocars;
- the tracked trajectory and navigation course: nature and severity of constraints and falls-off;
- the required function: inspection, drainage, nursing, excision, drug releasing, etc.;
- the duty programming and operation control support, provided by *robot* technologies.

Up now, the medical area differs from standard instrumental robotics due to task criticality, and this, generally, aims at developing *co-operative* tools, leaving on-process overseeing and command under the operator responsibility. This leads to conceive *co-robots*, namely, co-operating devices, assisting the medical personnel by adapting the tool to the on-going task or fulfilling given duties in demand. The robotisation, accordingly, tracks different scopes, such as:

trajectory planning, with constraints on the tip and along the (articulated) arm;

surrounding recognition, with assessment of the on-progress task achievements;

duty-cycle acknowledgement, with safety protection and reliability up-keeping.

The support helps the medical operators to follow safe paths by shape adaptivity, to fulfil gentle handling by controlled motion and to safeguard in-body integrity by high miniaturisation.

2.2. *Externally handed probes*.

This is a very extended family of devices, including several assisted endoscopes and actuated catheters. A very short mention addresses a few existing equipment.

London neuro-endoscope. The equipment is a 3 DoF neuro-endoscope, with parallel lay-out, derived from Steward platform (Figure 1). The hand-held tool [1], equipped with force feedback, help inserting a needle to the pathology depth; then, following the tract with the endoscope, the needle is guided to the site found by pre-operative MR images. With the roboscope aid, tumours and haematomas are reached with an accuracy of 25 μm. Recent tests involve robots, inserted through a small puncture in the skull, and guided all the way to the brain, through blood vessels as narrow as 1.5 mm in diameter.

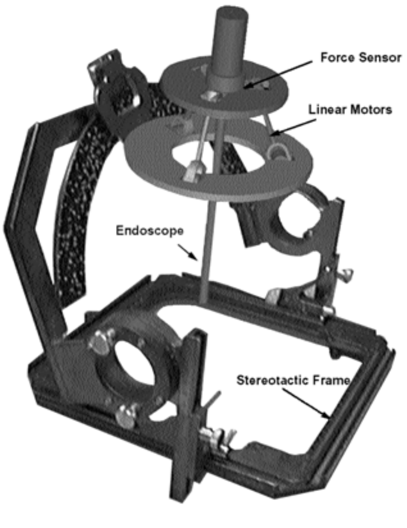

Fig.1 –London neuro-endoscope

Paris intestinal endoscope. The Laboratorie de Robotique de Paris (L.R.P.) endoscope (Figure 2), is made by a series of modules articulated to each other by pin joints; the connections are alternatively oriented at 90° to allow a 3D motion [2], [3]. On every link, two SMA springs have antagonist configuration to change the relative orientation. An integrated circuit controls the power supplied to the SMA. The outer diameter is 8 mm and the length is, due to its build-up, infinite. The LRP has developed interesting algorithms, to help the endoscope insertion.

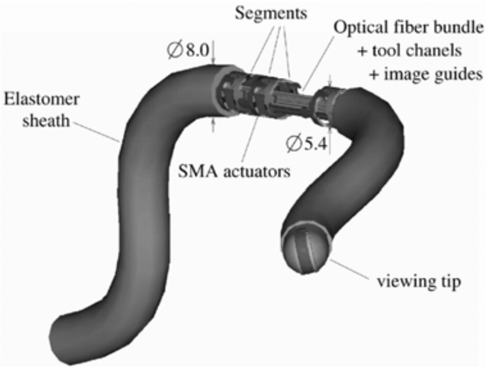

Fig.2 – Paris intestinal endoscope

Pisa arthroscope. The S. Anna laboratory arthroscope (Figure 3), helps the surgeon to drive the tools along an accurate path and to keep the desired tool position and attitude by respect to the anatomical structures [4]. To establish position and attitude, the rig avails itself of a commercial optical localiser, with three cameras placed over the surgical scene. The cameras detect IR pulses, emitted by LEDs on rigid frames solid to the objects to track, and the control unit computes, by means of geometrical triangulation, the coordinates of the tracked objects. This arthroscope has a cable-actuated multi-joint mechanical structure; it is equipped with a position sensor, measuring the tip attitude, and a force sensor, detecting the contact with delicate tissues in the knee; the overall error is 2.3 mm.

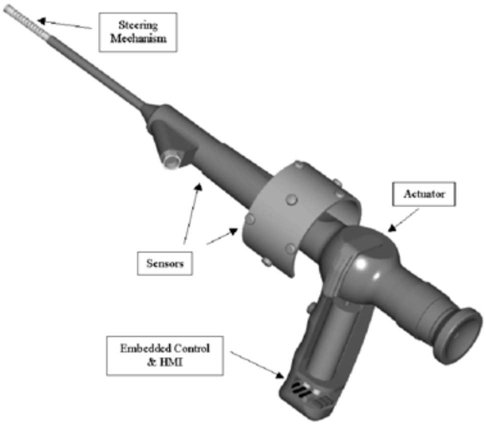

Fig.3 – Pisa arthroscope

2.3. ***In-body travelling worms***.

A *worm* is capable of independent motion, thus, it travels within (natural or artificial) ducts by means of suitable locomotion, enabled (normally) under remote control, according to sensor-driven local autonomy. The domain is quickly expanding, and some example developments are given.

Leuven intestinal worm. The intestinal worm (approximately 95 mm long, with 15 mm diameter) is made up by three segments (Figure 4): a locking part, an extensible part and a two degrees of freedom bending parts [5], [6]. The motion is provided by SMA, with bending obtained by a stack of links. Two bending prototypes, at least, have been built, respectively with 15 mm and 5 mm external diameter [7]. The lay-out follows binary mode control: each link includes a selection circuit to enable one or more DoF, by means of commands modulated by the power supply. The SMA actuation provides simple means to create a sequence of *grasp* either *extension* states, by means of a binary control supplying (electrical) power for the heating or the cooling processes.

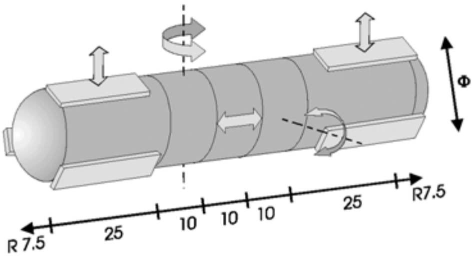

Fig.4 – Leuven intestinal worm

Pisa intestinal worm. The Multi-functional mini-robotic SYstem for endosCopy (MUSYC) project aims at colonoscopy [8]. The device (90 mm long, with 18 mm diameter), has three locomotion modes: ‘inchworm’, ‘sliding clampers’ and ‘colon inflating’ (Figure 5). The first resort to combined actuation, through a *clamper*, sticking at the wall and an *extensor*, providing positive extensions. The second avails of tendon stretching and two pairs of clampers; the colon-scope moves forward as a cliff climber by alternative grasps and body extensions. The last exploits sucking air where the worm has to go and pumping where is passed. For all solutions, clamping is obtained by tissue sucking and jaws pinching; 45° rotation is achieved, with 11 mNm torque supplied by 3 small SMA springs with a 120° lay-out; the cooling system is based on air re-circulation. The robot could by provided by two small surgical arms.

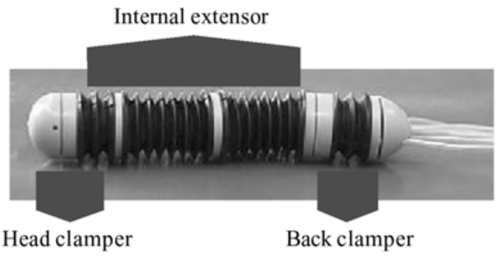

Fig.5 – Pisa intestinal worm

2.4. ***Navigating intelligent pills***.

The *intelligent* pill is a dream of smart medicine; it is swallowed by the patient, collects data concerning the patient health problem, makes analyses and diagnoses, then, finally, release proper medicine to cure it. The probe should be less than 10 mm; prototypes, able to monitor the intestine with a small camera, have already been created and tested. Motion strategies are analysed being relevant properties, even if, sometimes, the actual size could still be an hindrance. The following prospected studies are mentioned.

Japan intelligent pill. The RF System laboratory in Japan [9] has created the Norika3 pill (Figure 6). The miniature capsule contains the optics and the electronics; The dimensions are diameter 9 mm and length 23 mm. An additional light, inside the pill, allows to obtain better images of the digestive walls. The motion is assured by magnetic fields generated by a dress wore by the patient. The pill gives 30 images/s by radio signals. The capsule, for safety has no battery, the cost of a capsule is of about 100 dollars.

Fig.6 – Japan intelligent pill

Kentucky veins pill. The Narika3 pill is designed to explore the intestine; additionally scaling a similar device will allow to explore the veins. Leslie Rubinstein, from Renaissance Technologies, aims at a vessel, in the millimetre range, able to navigate inside the veins-arteries blood stream, and to locate and destroy tumours [10]. The propulsion is provided by the William McLellan electric motor (size of 0.397 mm^3), through vibrating cilia (similar to those of paramecium). Cancerous cells are burn away, using an high-powered laser diode by vaporizing the unwanted tissues. Samples of the blood plasma can be tested inside a closed chamber, with the ability to do chemical analyses.

3. EXAMPLE DEVELOPMENT AND CONCLUDING COMMENTS.

Up now surgery did develop heavily exploiting the individual ability of the front-end operators, with technical refinements step by step included, slightly altering the trend by steady betterments. A similarly smooth entry is expected with robotics; new opportunities need be acknowledged as *smart* technique, then proper experimentation and training would turn them into reliable issues. On these premises, preliminary step of surgical robots is to show the feasibility of a modular lay-out, assuring body penetration by curved and twisted paths with minimal impact. For abdominal theatre, the rig outer diameter shall not exceed 10 mm, with 200 to 300 mm total length; the wrist, to carry extended sets of effectors (scalpels, scissors, sewing rigs, cameras, etc.), needs accept dexterous set-ups (e.g., cameras carriers) and heavy-duty rigs (e.g., scalpels grippers).

The concepts are dealt with to sketch a proposal. The poly-articulated snake-like arm, is obtained replicating a series of blocks, with re-settable joints, and the final shape is given, modifying the coupling of the actuated joints [11]. Different options are studied: - one degree-of-freedom blocks, with an elastic joint and a micro DC motor (Figure 7); - two degrees-of-freedom blocks, with spherical joints and lateral strings driven by outer motors (Figure 8); - two degrees-of-freedom blocks, with locally actuated universal joints (Figure 9). The final rig exploits three to six blocks. Alternative wrists are also dealt with, including a compact parallel-kinematics, three degrees-of-freedom spherical lay-out. Specifically task-oriented end-effectors are considered, e.g., a self-operating sewing device, capable to operate with a single thread.

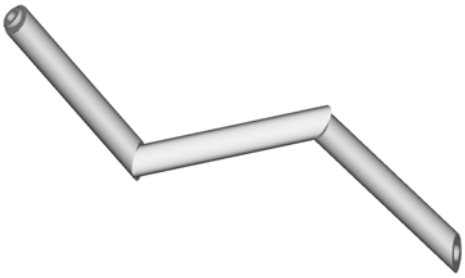

Fig.7 –1 DoF modules snake

Fig.8 –2 DoF module snake

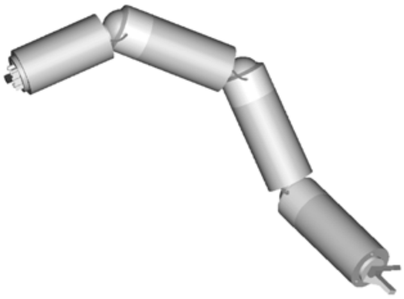

Fig.9 –Spherical joints snake

The project is covering the concept design and feasibility is assessed on digital mock-ups, by virtual tests for current operation conditions. Two running modes are addressed: - remote operation, through master-slave coupling, in order to achieve pre-set theatres; - programmed operation, once the surgical sequences are identified. With the former mode, visual, aural, force and tactile feedback is provided and *fiducials* are tracked, to establish reliable and accurate settings. The latter mode autonomously performs special duties (scalpel sequences, legation knitting, etc.), within *machine* tolerances. The different pieces of the modular lay-out are chosen among existing components, and the test environments refer to data derived from similar missions.

Architecture modularity is basic requirement to compare alternatives. The actuation technology deserves critical attention, distinguishing: - shape control, to model the rig for the duty; - effectors power supply, for the planned operation. The survey shows that, mainly, four options are addressed to model out the arm shape:

- strings with antagonistic springs: quite simple lay-outs, providing homogeneous power supply to the effectors, when required; size limitation is principal drawback;
- shape memory alloys: really popular option; biggest hindrance is the time delay, as the switching requires given temperatures, reached by heat exchanges supplied by (small) electrical powers;
- piezoelectric materials: quite reliable opportunity, actually limited by tiny overall power feeding and comparatively small induced strains;
- electrostrictive polymer artificial muscle: innovative technique, requiring further assessments.

The evolution in the field is expected to be quite fast and, even, to accelerate, yielding totally new sensors and actuators. Thus, rather than technicalities, fully-consistent operation lay-outs need be conceived leading to new tools and providing self-sufficient testing theatres of innovative ideas. In this frame, the thoracic or abdominal surgery are worthy reference surroundings, not immediately requiring very high miniaturisation, still, directly providing test beds for the alternative approaches of robotics. To that purpose, the prospected lay-outs specifically aims at architectures and operation settings, with attention on fully developed virtual prototypes to properly look after actual options, whether or not inherent with anthropocentric habits.

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