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Design of a telemanipulated system for transluminal surgery ‡

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Abstract— **Flexible endoscopes have been recently used for new surgical procedures called NOTES, i.e. Natural Orifice Transluminal Endoscopic Surgery. However, the movements of conventional flexible endoscopes are limited and surgeons can only perform basic tasks with these systems. In order to enhance endoscopes possibilities and workspace, several solutions have been proposed to redesign the whole endoscopic system. New devices have been proposed recently which are made up of a classical endoscope basis with two additionnal arms. However, these mechanical devices are not completely adequate to properly perform NOTES. That is why we are currently developing a robotized system which can be simultaneously teleoperated while performing autonomous motions. This article presents the constraints of transluminal surgery, existing devices and our new system together with its mathematical modeling.**

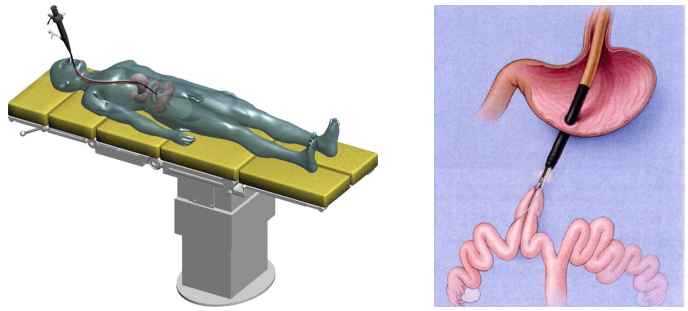

Fig. 1. Principle of transluminal surgery

I. Introduction

NOTES (Natural Orifice Transluminal Endoscopic Surgery) is a new surgical technique, which consists in reaching the peritoneal cavity through a natural orifice (mouth, anus or vagina) in order to treat a specific area (Fig.1). It allows to perform various procedures such as cholecystectomy or tubal ligation. The main advantage of this kind of surgery is the absence of visible scars since it does not need any external incision. Moreover, incisions in internal membranes required to reach abdominal cavity, have the particularity to heal quickly. Thanks to this procedure, post-operative pain, recovery time and psychological impact are reduced. More than 20 of these procedures have already been performed on human beings in Strasbourg [1].

The equipments currently used for NOTES are flexible endoscopes from gastroenterology. These endoscopes are composed of a long flexible shaft, more than one meter long, with an articulated bending tip. The bending tip is about ten centimeters and can move along two perpendicular directions. The tip is linked to navigation wheels thanks to cables running along the shaft of the endoscope. The surgeons control the motion of the tip by turning the navigation wheels. Visual feedback is provided by a miniature camera embedded at the tip.

Transluminal procedures are challenging for surgeons. Indeed the position and the shape of the flexible shaft of the endoscope cannot be controlled. The shape is defined by the anatomical constraints, that is to say anatomical structures in contact with the endoscope. The surgeons do not know this shape and every movement of the body of the endoscope leads to unpredictable effects in the images. Moreover, the lack of degrees of freedom (DOFs) limits the use of classical endoscopes to a few basic tasks, while complex tasks, such as stitching or knot tying, are very difficult or even impossible to perform. Hence, surgeons need additional degrees of freedom and better manipulability. That is why new endoscopic systems with articulated arms have been recently proposed, which provide at least two additionnal degrees of freedom for each arm. With this new kind of system, the workspace is increased and surgeons can perform more complex surgical tasks in a more intuitive way.

This paper presents a new robotized endoscopic system for NOTES. The paper is organized as follows. In the following section a review of the different issues and constaints of NOTES are exposed. In section III a review of the existing systems is presented. Section IV describes our prototype and how it has been robotized. Finally modeling details which can be used to control and optimize the design of the system are provided in section V.

II. Problematics

Currently available flexible endoscopes are inadequate for performing complex transluminal surgical procedures. Issues with conventional scopes include :

- the insufficient triangulation angle between the surgical instruments,
- the lack of a multitasking platform which allows the operator to perform several tasks independently, such as holding an instrument and grasping an organ,
- the limited number of access channels for driving surgical instruments to the operation area,
- the limited number of available DOFs and
- the inability to properly control surgical instruments.

A long term solution would be to redesign the flexible endoscopic system. However, flexible endoscopes are widely

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Fig. 2. Experiments carried on at the IRCAD in Strasbourg using a manual transluminal system.

used systems which allow to overcome several difficult problems such as cleaning, asepsis and good visual feedback. Therefore they are a good basis for developing more complex systems. Several prototypes have been proposed and are currently tested [2]. The design which has been widely chosen consists of a video endoscope and two arms. The arms are attached to or included in the main endoscope. In all systems, the distal DOFs can be controlled from the proximal end of the system using cables. Other difficulties, consequences of the previously mentioned problems, have arisen during surgical procedures. Indeed, once the target has been reached, the surgeon must combine several actions to achieve adequate motions. Given the high number of DOFs, several surgeons must cooperate for carrying out a task (see Fig.2). They share a small workspace and must show a good coordination to perform the operation.

III. Related work and systems

In the following, we briefly review some of existing systems and their specificities. The non-exhaustive list of systems we compare is made-up of systems developed in university laboratories (the endoscopic robotic system from Jikei University, Tokyo- Japan [3], the Nanyang University endoscopic system, Singapore [4], and the HVSPS from the Technical University in Munich [5]) and industrial prototypes (the ViaCath from HansenMedical [6], the Cobra system from USGI Medical , the Anubiscope from Karl Storz endoscopy which has been very recently presented at the SAGES congress, and the system proposed by Olympus [7]. They can be classified according to several criteria.

a) Use of an overtube: Several systems use an overtube with three channels [Cobra, Tokyo University, ViaCath, Nanyang University, Munich University]. One channel is used for passing a flexible endoscope which brings light and visual feedback, and the other channels are used for instruments. This overtube is generally passive and flexible. However the overtube of the ViaCath system can be controlled along two directions at the tip. The overtube of the Cobra system is flexible but it can be locked in shape (see Fig.3).

Fig. 3. Cobra system by USGI Medical, Inc

For the other systems [Storz, Olympus] the light and visual feedback is direclty brought by the main system (see Fig.5(a)). There are only two channels in the system for passing instruments and the tip of the main endoscope is controlled.

b) Articulated or passive instruments: A key difference between the systems concerns the use of specific articulated instrument or conventional passive instruments. In most systems [Tokyo University, ViaCath, Nanyang University, Munich University], a part of the DOFs is directly provided by the surgical instruments through discrete or snake-like joints. However, in the Olympus and Storz systems, instruments are passive. A part of the DOFs is brought by hollow arms. The surgical tools are inserted inside the arms, which are in turn inserted inside the channels of the main system [Storz] or direclty fitted at the tip of the main endoscope [Olympus].

c) Discrete or continuous DOFs: Most of the systems use snake like continuous DOFs as in classical endoscopes. However, discrete DOFs are used for the instruments in the Nanyang University (shown in Fig.4) and in the ViaCath system. These are also actuated using cables as in continuous snake-like systems.

d) The triangulation problem: The triangulation of the instruments is a key feature for good operating conditions. Triangulation is generally brought by deflecting the instruments from the main endoscope direction [Olympus, Munich, Tokyo]. In the ViaCath system, the triangulation is provided by the multiple DOFs of the instruments. The Storz prototype proposes an original solution based on the use of articulated flaps at the tip of the endoscope. Closed flaps allow the insertion of the endoscope into the human body. When opened, the flaps deflect the tip of the channel and hence the surgical instruments, thus allowing the triangulation of video and arms (see Fig.6).

e) Manipulation and Robotization of the systems: Specific master consoles have been proposed to manipulate these complex devices. They allow for a single surgeon to control the whole slave system and to perform the surgical task. In order to make the manipulation of the system easy and intuitive, Olympus offers a control interface which is

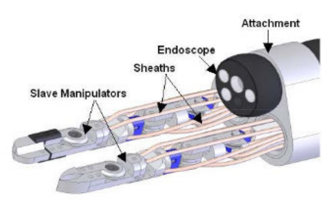


Fig. 4. Nanyang University prototype

(a) (b)

Fig. 5. (a) Olympus device (b) Olympus control interface by

Fig. 6. Karl Storz system and its control handles

similar to manual 4DOFs laparoscopic surgical instruments and allows to mechanically drive the arms (Fig.5(b)).

But among the presented systems, only the ViaCath and the Singapore systems have been motorized. An exoskeleton interface has been proposed to easily control all the DOFs of the Singapore system.

IV. Presentation of our endoscopic prototype

We have developed a new endoscopic system. The main objective is to propose a teleoperated system that allows a single surgeon to perform complex NOTES procedures. Our prototype solves the triangulation problem. At present time the whole setup has been constructed, all the components of the robot have been mounted. The mathematical model has been partially solved and is being implemented on the system for testing.

A. The mechanical system

The slave system has been developed in collaboration with Karl Storz[1] based on the manual system briefly described in the previous section. Our prototype consists of two flexible hollow arms which are attached to a conventional flexible endoscope with 2 DOFs. The endoscope provides the optical system for visual feedback and two working channels for conventional instruments. The hollow arms are fixed on the circumference at the end-part of the bending tip of the endoscope using a specific cap. Each arm provides 2 DOFs similarly to the main endoscope : left/right and up/down motions. Surgical instruments can be introduced into the arms and guided to the operating area. These instruments can translate and rotate inside the arms. The cap attached to the endoscope also allows to deflect the arms from the main direction of the endoscope. This provides triangulation between the arms and the endoscopic view, it enhances the cooperation area of the two arms and makes the use of the system more intuitive. A view of the tip of the prototype is presented in Fig.7.

[1]Karl Storz Endoskope GmbH, Germany

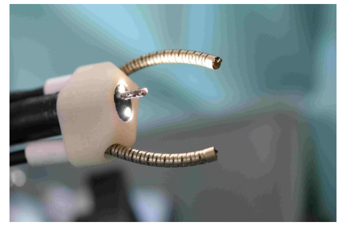


Fig. 7. The tip of the prototype with the special end cap.

B. Motorization

The orientation of the main endoscope as well as the orientation of both arms is driven by two cables which run through the flexible shaft up to the proximal end where they are rolled up around pulleys.

These pulleys are controlled by rotary motors mounted on the endoscope and the arms handles (see Fig.9). So as to choose the solution for the motorization, the torques required to bend the tip of the main endoscope and the arms have been estimated. The results of the torque assessment are given in table I. The motor which drives the main endoscope orientation must also be able to bend the passive flexible body of the arms.

The smallest available motors allowing to reach these torques have thus been chosen off-the-shelf. These are Harmonic Drive FHA-8C hollow shafts motors which allow up to 1.5Nm torque for the main endoscope (shown on Fig.10) and Harmonic Drive RSF for the arms.

The instruments are translated into channels and into arms thanks to linear motors. Moreover, a rotary motor can be mounted onto the translation unit so as to rotate the surgical instruments around their own axis (see Fig.8).

Finally, the whole system can have up to 12 actuated DOFs which can be combined in several manners and can hence provide solutions to many medical procedures.

All motors are velocity controlled at low-level with external position loops running at 2000Hz on a unique controller. A low bandwidth loop running at the frame rate of the endoscopic camera can be added for providing image-based control of the system.

C. Master control of the system

The surgeon console looks like a desk workstation. It carries two master interfaces and two flat panel monitors for displaying the images of the endoscope and other visual

	Max req. torque	motor	max. continuous mot. torque
Main endoscope	1.3Nm	HD FHA	1.5Nm
Hollow arms	0.20Nm	HD RSF	0.45Nm

TABLE I

Choice of the motorization solution

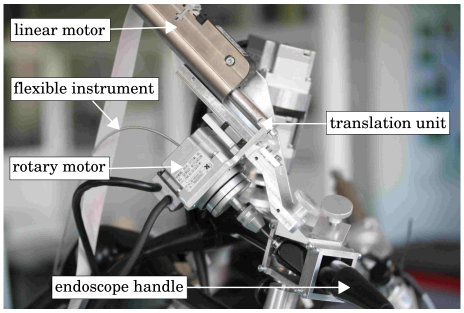


Fig. 8. Translation and rotation system of the instruments

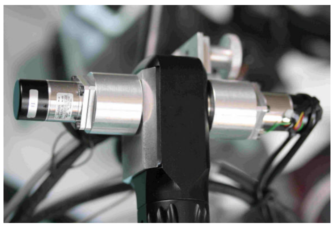


Fig. 9. Motorization of the arms

information. The master interfaces are Omega interfaces by ForceDimension which provide 7 DOFs each (shown in Fig.11). Given the number of DOFs, it will not be intuitive for the surgeon to control each DOF separately. Several solutions are possible based on the cartesian control of the tip of the instruments, either in the endoscopic camera frame or in the base frame of the endoscope. The rotation and the translation of the instruments inside the hollow arms or the channels are decoupled from the other DOFs and can be controlled separately.

D. The whole setup

Despite the choice of the smallest and lightest equipment, the system cannot be easily carried by a surgeon. That is why a carrying cart has been designed. This cart contains the motors amplifiers and controllers and supports a passive XYZ positioning table. Three passive arms which hold the motorized handles are magnetically fixed onto the platform. One arm carries the endoscope handle, its motorization and the motorization of the instruments (translation and rotation) inside the channels. Each of the other arms carries the handle of the hollow arms and its motorization as well as

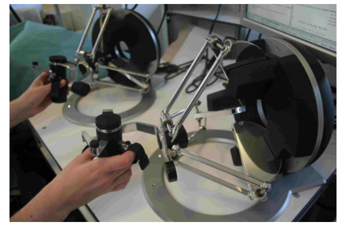


Fig. 11. The master interfaces of the prototype

the motorization (translation and rotation) of the instruments inside the hollow arms. The whole setup is illustrated by Fig.12.

A transluminal operation using our device can be described as follows.

- First the surgeon positions the master console at the most suitable place to perform the operation.
- Then the main endoscope is inserted into the body of the patient up to the operating site. The endoscope is manually driven at the proximal part and the orientation of the bending head is controlled using a joystick.
- The cart carrying the slave system is placed at the extremity of the operating table and the handle of the endoscope is fixed on the slave console.
- The position of the base of the slave system can be adjusted with respect to the patient thanks to the XYZ platform or the passive arms. Then the arms are inserted into the patient body.
- Surgical instruments can then be inserted inside the hollow arms and in the endoscope channels according to the medical requirements.
- From then on the motions of the system are controlled using the master consoles. However, if the whole system must be moved during the operation, it is possible to manually move either the XYZ platform, the passive arms or even the slave cart.

E. Solutions and Advantages

Our system presents several advantages. The arms have the same design than the main endoscope. The positioning of the tip of the instruments is more intuitive than for the initial manual system which requires to spin the whole arm, what can be difficult to figure out beforehand. The endoscope channels are larger than the arms and allow to insert bigger

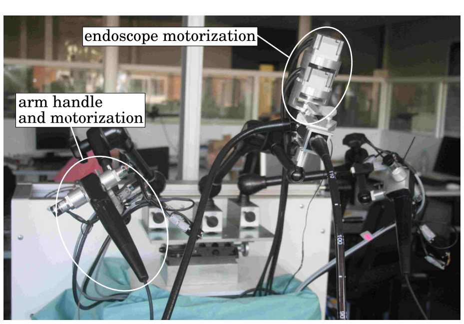


Fig. 10. Motorization

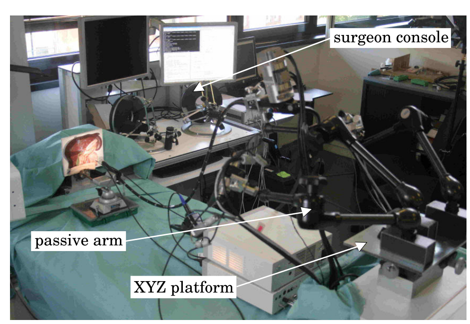


Fig. 12. View of the whole setup.

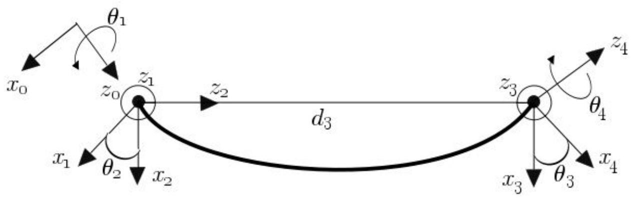


Fig. 13. Modeling of a flexible and continuum section

	θ_i	d_i	α_i	a_i
$0-1$	θ_1	0	$-\frac{\pi}{2}$	0
$1-2$	θ_2	0	$\frac{\pi}{2}$	0
$2-3$	0	d_3	$-\frac{\pi}{2}$	0
$3-4$	θ_4	0	$\frac{\pi}{2}$	0
$4-5$	θ_5	0	0	0

TABLE II

DH TABLE OF A FLEXIBLE SECTION

instruments which can be used to handle organs. Finally, the main advantage is the use of traditional instruments. Indeed, by using articulated arms rather than articulated instruments, it is possible to easily change instruments during the procedure.

The use of an intuitive master console is not sufficient. Physiological movements such as breathing motion add disturbances on the endoscopic system. The correction of these disturbances requires a complex coordination between what the hand of the surgeon controls and the motion seen in the image. That is why the endoscopic system has been robotized. Indeed, the aim of this robotic project is to teleoperate the system using master consoles while implementing automatic tasks such as visual servoing as proposed in [8]. It will also be possible to propose several working modes where surgeons could choose between dissociated motions of the arms or simultaneous use of the different elements of the endoscopic system.

V. MODELING OF THE SYSTEM

The kinematic model of the system is required for providing intuitive control of the system to the surgeon. Moreover, it can be used to refine the kinematic design of the system, especially the deflection angles provided by the end cap.

A. Model

The bending parts of the endoscope and the arms can be assimilated to "continuum robots" since they do not exhibit any discrete joints. In [9], an interesting modeling of this kind of robot is proposed. Under the assumptions that the curvature of the continuum section is constant, that the section is inextensible and that the wires are equally spaced on the bending section circumference, a continuum robot can be modeled thanks to discrete joints, represented in Fig.13. Thus, Denavit-Hartenberg (DH) convention can be used but interdependent DH parameters appear. This modeling can be used for the main endoscope as well as for the arms representation.

The DH parameters (from table II) can be linked to the geometric parameters of the bending section by the following relations:

$$\theta_1 = \varphi \qquad \theta_2 = \theta_4 = \theta = \frac{kL}{2} \tag{1}$$

$$d_3 = \frac{2}{k} * sin(\theta) \tag{2}$$

$$\theta_5 = -\varphi \tag{3}$$

$$\theta_{1i} = \varphi_i \qquad \theta_{2i} = \frac{k_i L_i}{2} \tag{4}$$

$$d_{3i} = \frac{2}{k_i} * sin(\theta_{1i}) \tag{5}$$

$$\theta_{5i} = -\varphi_i \qquad \text{with} \qquad i \in \{B, C\} \tag{6}$$

where k is the curvature of the endoscope bending section, L the length of this section and φ the orientation of the bending plane. k_B, φ_B and L_B (resp. k_C, φ_C and L_C) refer to the same parameters for the arm B (resp. arm C). To these geometric parameters one must add I_B and θ_B (resp. I_C and θ_C) which are the translation and rotation of the instruments into the hollow arms.

The angle φ and the curvature k can be related to the length distribution of the two wires ΔL_1 and ΔL_2 by the following equations:

$$k = \frac{\sqrt{\Delta L_1^2 + \Delta L_2^2}}{Lr} \tag{7}$$

$$\varphi = atan2(\Delta L_2, \Delta L_1) \tag{8}$$

where r is the endoscope radius. The arms follow the same geometric scheme:

$$k_i = \frac{\sqrt{\Delta L_{1i}^2 + \Delta L_{2i}^2}}{L_i r_i} \tag{9}$$

$$\varphi_i = atan2(\Delta L_{2i}, \Delta L_{1i}) \qquad \text{with} \qquad i \in \{B, C\} \tag{10}$$

where r_i is the arm radius.

The last step consists in expressing the relation between the length modification of the cables and the actuator positions $q = [q_1, q_2, q_{1B}, q_{2B}, q_{1C}, q_{2C}]^T$:

$$\Delta L_i = R_p * \Delta q_i \tag{11}$$

$$\Delta L_{ij} = r_p * \Delta q_{ij} \tag{12}$$

$$\text{with} \qquad i \in \{1, 2\} \qquad \text{and} \qquad j \in \{B, C\} \tag{13}$$

where R_p and r_p are respectively the radius of the endoscope pulleys and of the arms pulleys.

The complete system is a tree-like robot with two end effectors (Fig.14). This means that both arms have a common kinematic chain. Thus we can draw up both geometric and kinematic models. They are necessary to study the movement, the behaviour and the singular configurations of the prototype, but also to optimize the kinematic design of the system.

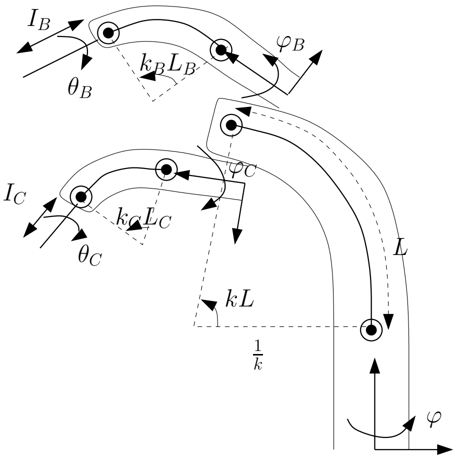
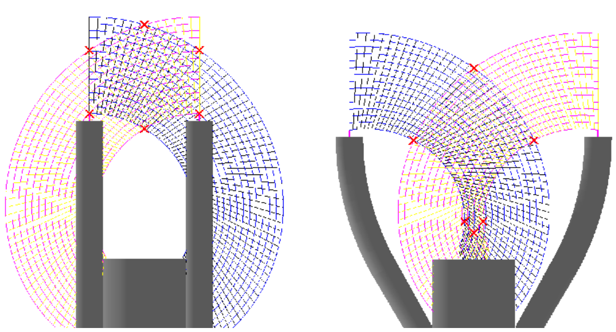


Fig. 14. Model of the head of the proposed system with 10DOFs. Instruments in the working channels of the endoscope are not represented.

B. Triangulation analysis

The modeling is helpful to analyze the effects of arms triangulation. One of the key components of our system is the end cap which allows the deflection of the arms from the main endoscope direction. Thanks to the models, we are currently analyzing the effect of the cap angles on the working cooperation area of the arms. The objective is to optimize this area to provide a maximum workspace to the user.

For instance, one can observe on Fig.15 that the cooperation area, A, defined by the intersection of arms workspaces (crosses on graphics), is larger when the deviation angle, ψ, is non null. We have used an optimization algorithm to define the best deviation angle. For instance for $L_B = L_C = 2cm$, the largest cooperation area is obtained for $\psi = 27^o$.



$\psi = 0$ $\quad$ $\psi = \frac{\pi}{6}$

$A = 193.55mm^2$ $\quad$ $A = 212.08mm^2$

(a) (b)

Fig. 15. Optimisation of cooperation area

VI. Conclusion and Future Work

NOTES appears as an important breakthrough for the future of non-invasive surgery. New designs of endoscopic systems is an important track for improving surgical possibilities in this field. Robotization also appears as a requirement given the high number of DOFs the surgeon has to manage. The teleoperation system we present in this paper provides triangulation of the arms for good working conditions, and will allow several working modes coupled with automatic tasks. It has the potential to allow tasks such as stitching or knot tying. However, improvements have to be performed based on the modeling analyzis and on preliminary experiments. First in vitro experiments show that the autonomous translation of the whole system could be a valuable add-on. Future in vivo validation trials are planned using the entire system.

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