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A modular magnetic platform for Natural Orifice Transluminal Endoscopic Surgery

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***Abstract*—Modern surgery is currently developing NOTES (Natural Orifice Translumenal Endoscopic Surgery) robotic approaches to enable scarless surgical procedures. Despite of the variegated devices proposed, they still have several limitations. In this work, we propose a surgical platform composed of specialized modules, in order to provide the overall system with adequate stability, dexterity and force generation. The concept behind the platform, the main modules and their performance are described to highlight the system potential to outperform current NOTES procedures.**

***Index Terms*—Endoluminal surgery, modular robot, NOTES**

I. Introduction

The current trend in surgical research mainly consists of reducing procedure invasiveness by decreasing the number and size of surgical accesses. Since its first description by Kalloo et al. in 2004 [1], NOTES has been attracting growing interest because it potentially eliminates abdominal incisions in the diagnosis and treatment of abdominal pathologies, by combining endoscopic and surgical techniques. Two main approaches are being explored for NOTES procedures: multifunctional endoscopes [2] – [4] or entirely insertable robotic platforms [5], [6]. Although multifunctional endoscopes are generally well-accepted within the surgical scenario, they still lack dexterity and mechanical stability [7]. Moreover, if additional assistive tools larger than the working channel of endoscopes are necessary, they can be only inserted through laparoscopic incisions . On the other hand, several endoluminal mobile robots have been proposed and demonstrated in transgastric and transvaginal procedures [8]. Despite of the preliminary results described in literature, the main drawbacks plaguing these platforms are related to safety issues, high system encumbrance, limited generated forces and poor mechanical stability. In order to overcome these limitations, we propose a modular magnetic platform for NOTES procedures composed of a trans-abdominal magnetic frame for robotic module anchoring, dedicated miniaturized surgical tools and a magnetically-actuated retraction system (Fig. 1).

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The proposed platform was conceived according to a modular approach for increasing both overall flexibility and versatility. By exploiting the proposed approach, different robotic tools should be inserted and used depending on the surgical task. Each module is designed for carrying out specific functions exploiting dedicated actuation mechanisms (i.e. magnetic actuation, Shape Memory Alloy – SMA actuation and embedded miniature motors), as described in the following sections. All robotic modules are conceived to keep the access port as much free as possible for the insertion of additional robotic tools and/or the endoscope, which is used as an assisting tool for improving procedure safety and controllability.

The aim of this study is to demonstrate the platform capabilities: the system features will be analyzed and its design will be compared with the state of the art.

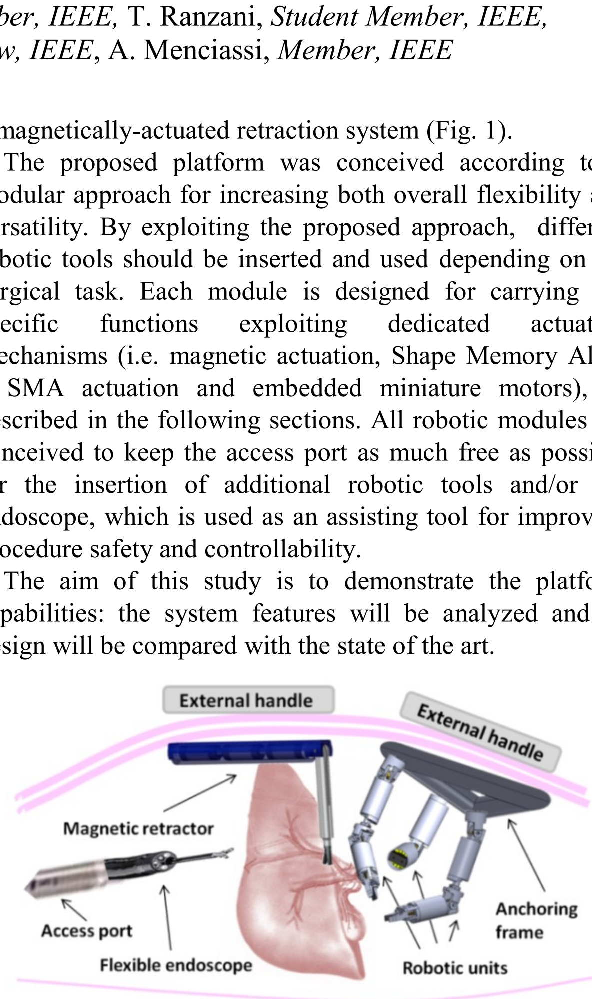

Fig. 1. Schematic representation of the modular platform including the magnetic anchoring frame, modular robotic units and magnetic retractor. All modules are delivered through the access port and are positioned using a flexible endoscope.

II. System Overview

A. Trans-abdominal anchoring frame

A triangle-shaped device, magnetically anchored to the abdominal wall by means of an external magnetic hand-held structure, was conceived as a stable base for robotic modules to be docked or un-docked during surgical procedures [9]. In order to improve stability, the anchoring frame was designed to embed a large number of permanent magnets, but still preserving the possibility to be delivered through an esophageal access port (17 mm internal diameter overtube, Guardus, US endoscopy, USA) suitable for transgastric

NOTES procedures. As additional design requirement, the device should have a wide contact surface capable of distributing the magnetic forces on the internal abdominal wall, and enough space on board to house dedicated miniaturized mechanisms (i.e. for vision, retraction, suturing or other dexterous robotic tools for different tasks).

A configuration-change actuation mechanism has been selected to fulfill these requirements. The device configuration can be actively changed from an extended cylindrical shape (compliant enough for deployment, Fig. 2 bottom) to a compact triangular one (rigid for supplying stability to docked surgical tools, Fig. 2 top-left). Thus, an SMA angular actuator was designed and validated [10]. The SMA actuation mechanism was chosen for several reasons: compact size, low cost, compatibility with magnetic fields, muscle-like behavior allowing soft interaction with tissues, and compliance during system deployment. In addition, SMAs only need two electric wires for power supply (up to 2.5 W for configuration change only), leaving the lumen of the insertion port practically free for introducing the endoscope and for delivering additional surgical robotic units to be docked onto the SMA frame or to be deployed into the abdomen (such as the magnetic retractor as in Fig. 1).

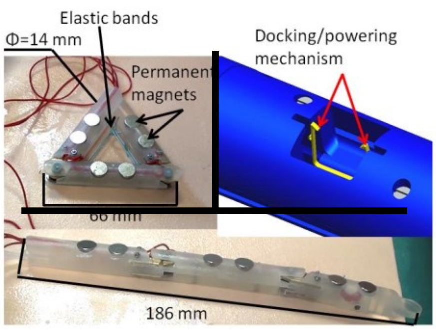

Fig. 2. Trans-abdominal anchoring frame in working (top-left) and extended (bottom) configurations; 3D sketch of the docking mechanism (top right).

In the final prototype (Fig. 2, top left), two elastic bands were exploited as actuator bias elements. They are also used as a safety countermeasure in the event of device malfunctioning: the elastic band can be cut using a flexible endoscope so that the device can be safely straighten and extracted in case of electronic failure. The trans-abdominal anchoring frame has a diameter of 14 mm, a total length of 186 mm in extended configuration and a total mass of 48 g. For magnetic coupling with the external handle, the frame embeds 6 cylindrical magnets placed on the upper part of the system.

The current configuration has been simulated exploiting FEM software (COMSOL Multiphysics) and it resulted to sustain up to 500 g considering an abdominal wall thickness of 25 mm. The reported values have been also experimentally verified. On the bottom part of the frame, dedicated helical SMA springs actuate 3 docking and un-docking mechanisms to house the modular surgical units.

Magnetic instruments tested on animals [11] demonstrated that a pressure up to 46.75 kPa, with an inter-magnets distance of 9 mm, does not generate histological damages in the abdominal wall. According to these requirements, the magnetic attraction force at 9 mm distance was evaluated for the anchoring frame. The resulting value obtained from numerical and experimental assessment is 21 N; considering the triangle geometry, the resulting pressure is 15.17 kPa (i.e. mush less than 46.75 kPa).

B. Modular robotic units

The modular robotic units were designed to fit the dimensional requirements of an esophageal access. The concept of basic modules that can be assembled together was originally introduced in [12], and this led to robotic units sharing a basic design, but provided with different functions depending on the assembly procedure.

Internal actuators were employed for the modular robotic units in order to provide them with multiple DoFs (Degrees of Freedom). Brushless micromotors (SBL04 by Namiki, Akita, Japan, reduction ratio 1:337) were selected for the actuation. The mechanisms of the module joints consist of a helical gear mounted on a worm gear to obtain pitch motion, and two spur gears as a reduction stage to obtain roll motion. This solution provides each module with 2 DoFs (35 mm in length and 12 mm in diameter). The motors, their respective mechanisms and the control board are integrated in each module. Once anchored to the frame, the robotic units are able to move according to its specific features. Power is delivered to the modules through two 0.15 mm electric wires per module. The basic robotic units included in the experimental assessment of the platform were a 2 DoFs image acquisition unit, a 4 DoFs manipulator unit and a 2 DoFs gripper unit.

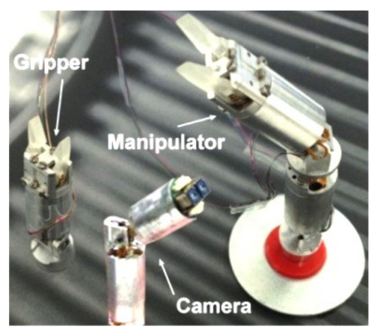

Fig. 3. Assembled prototypes of the modular robotic units.

The image acquisition unit consists of a miniaturized camera robot which provides stereoscopic images during the surgical procedure [13]. It includes the basic module, a passive support for the stereoscopic camera (UXGA, 30 fps, by ST Microelectronics, Milano, Italy) and a Light Emission Diodes-based illumination system (LEDs, NESW007BT, Nichia, Tokyo, Japan). The 4 DoFs manipulator (78 mm in length and 12 mm in diameter) was designed by assembling two modules with a pitch-roll-pitch gripper kinematic chain, finally producing 0.65 N as tip force. An additional robotic unit for basic manipulation tasks (i.e. the gripper module) generating up to 1.20 N force on tip was manufactured. Force experiments were performed using a commercial 6-

axis load cell (Nano17, ATI, Industrial Automation, USA) having a resolution of 0.0139 N. The robotic units are shown in Fig. 3, resembling an architecture with left and right tools and a central stereo camera. The three robotic units can be delivered transgastrically and assembled on the docking areas of the magnetic anchoring frame thus providing bimanual manipulation and stereoscopic vision of the specific operative region. Other robotic units with different end-effectors can be re-assembled by exploiting the docking and un-docking systems of the anchoring frame, depending on the surgical task to be addressed. Docking and un-docking processes are assisted by a flexible endoscope (see Fig. 1, on the left).

C. Magnetic retractor

Retraction tasks are needed during most surgical procedures to lift organs accordingly to the surgeon needs [14]. This task is generally performed using a dedicated instrument that is held by the surgeon assistant through a trocar; for this reason it is extremely challenging in a pure NOTES approach. The main requirements of the retractor module are high force for organ lifting and stable anchoring, while high precision is less critical. Considering the technical difficulties of integrating and managing electronic components and motors in terms of bulkiness, electrical wires and control, the proposed retraction module allows for simple and effective lifting of the internal organs. It exploits magnetic interaction both for positioning the system in the desired area and approaching the organ for tissue grasping without any internal motorized mechanism. The retraction module proposed for our platform exploits magnetic interactions without the need for a dedicated port and can be delivered in the operating area through a NOTES access.

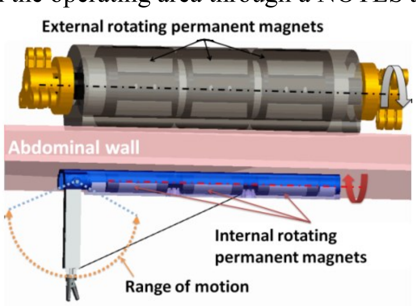

Fig. 4. 3D sketch of the retraction module and its components.

Magnetic actuation is exploited to perform both retraction and organ shifting. The retraction module (Fig. 4) is composed of an external handle and an internal module. The external handle hosts 3 cubic permanent magnets (30 mm side) which can rotate around the axis parallel to the abdomen. The internal frame has a tubular shape of 14 mm in diameter and 190 mm in length. It hosts 3 cylindrical, diametrically magnetized permanent magnets, and has a cable actuated joint. Joint actuation is performed by winding and unwinding cables on pulleys rotating together with magnets. Two cables are fixed at the opposite sides on the base of the gripper in order to guaranteed active bidirectional motion. By exploiting external magnetic actuation as described in [15], we induced rotation of the inner magnets based on rotation of the external ones.

The current configuration has been simulated using FEM analysis (COMSOL MULTIPHYSICS). According to the simulation results a torque of up to 0.2 Nm is transmitted to the internal magnets that are free to rotate inside the internal module. Therefore, the magnetic link between the external handle and the internal frame has the double function of actuating the internal joint and keeping the stable anchoring of the retractor with an axial force of 10 N, considering an abdomen thickness of 25 mm. The reported values have been experimentally verified to meet the pressure constraints on the abdominal wall. For this purpose, the magnetic attraction force at 9 mm distance, according to [11], has been assessed in 32 N. Considering the retractor geometry, this corresponds to a pressure on abdominal wall of 30.34 kPa, again lower than the 46.75 kPa safety limit.

Despite its simple design, if compared to state of the art magnetic retractors [16]-[21], the main advantage of this system is that organ lifting can be controlled by the magnetically actuated DoF, thus avoiding abrupt forces to be applied onto the tissues.

D. Embedded electronics

A wireless microcontroller (CC2430, Texas Instruments, Dallas, TX, USA) was chosen to control the motors described in Section II B and manage wireless communication between the active elements of the platform by exploiting a ZigBee architecture. A miniaturized board (10.8 mm diameter and 0.2 mm thickness) embedding the microcontroller and the motors drivers was designed to be integrated in the magnetic frame and into robotic units. Each board can control up to 2 brushless motors and 6 digital I/O ports can be devised for sensors and wired communication [22]. An intra-abdominal wireless network is set up for communication between the platform components. Each robotic unit communicates via wireless with the anchoring frame which manages the low-level control of the specific module and is interfaced via wires with the external control unit. The disturbances in wireless transmission through human tissues can be overcome since intra-module communication is confined inside the abdomen. This results in no need for a cabled data transfer, thus reducing the total number of wires, that is an advantage from a NOTES viewpoint.

III. Discussion and Conclusion

System design and component development were carried out with the final aim of setting up a surgical room in the patient's abdominal cavity by passing through the mouth, esophagus and stomach wall. Bringing different robotic units inside the human body allows a complete surgical procedure to be accomplished, whilst the anchoring frame and magnetic retractor provide for stability and tissue exposure, respectively. Different kinematic chains can be obtained by combining the basic modules described in Section II B, and

TABLE I
PLATFORM COMPONENTS AND FUNCTIONS

Component	Function & performance	DoFs	Communication
Magnetic anchoring Frame	· Anchoring · Docking/ Undocking · Low-level control · Intra-abdominal wireless network	· 4 (3 external magnetically driven, 1 SMA actuator on board for conf. change)	· Wired (internal-external communication) · Wireless (Intra-abdominal communication)
Modular robotic camera	· Stereoscopic vision	· 2 embedded motors (pitch, roll)	· Wireless (Intra-abdominal communication)
Modular robotic manipulator	· Manipulation (up to 0.65 N on tip)	· 4 embedded motors (pitch, roll, pitch, gripper)	· Wireless (Intra-abdominal communication)
Magnetic retractor	· Retraction (up to 4 N on tip)	· 4 external magnetically driven	·None

various robotic units can be interchanged when needed.

Each platform component was designed bearing in mind final integration in terms of actuation methods, size, interaction between components and compatibility with a narrow access port. The main characteristics of the platform components are summarized in Table I. The anchoring frame exploits SMA actuation, which is not affected by the permanent magnets used for anchoring. On the other hand, the operating distance between the modular robotic units docked to the anchoring magnetic frame is compatible with the use of electromagnetic motors. This makes it possible to finely operate the robotic camera, the gripper and the manipulators. Finally, the retractor unit exploits a purely magnetic actuation method and provides adequate force without the need for communication wires or power sources.

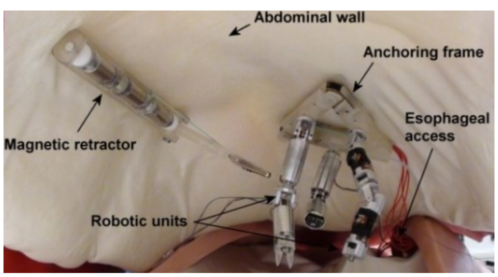

Fig. 5. Assembled NOTES platform in a human abdomen simulator.

The dimensions were chosen to meet the anatomical constraints needed to deliver and execute the surgical tasks required during typical surgical procedures. Magnetic attraction force has been demonstrated to be an effective and safe solution to guarantee stable adhesion to the abdominal wall. Moreover, no additional anchoring systems, e.g. needles, suturing or clips, are necessary for providing stability to the system.

The proposed system has been successfully delivered into the abdomen of a human simulator, as illustrated in Fig. 5. The modular approach described for the general platform of is highly flexible in terms of applicability and task feasibility, making our platform a valid approach for NOTES procedures, and introducing a novel technical solution as support to the most promising surgical procedures.

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