STIFF-FLOP surgical manipulator: design and preliminary motion evaluation

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***Abstract*—This paper presents a soft multi-module manipulator for minimally invasive surgery (MIS). The design and the materials are bioinspired and try to reproduce some biological capabilities of the octopus, such as elongation, omni-directional bending and stiffness variation. Embedded fluidic chambers allow to pneumatically actuate the manipulator in order to achieve a 3-D motion, while a variable stiffness mechanism based on the granular jamming phenomenon allows to control the stiffness of the arm. The design of three modules integration and the fabrication phases as well as a preliminary study on the 3-module manipulator performance are reported. Elongation and bending have been experimentally evaluated. The arm is 165 mm long and it is able to elongate up to 53.3% of the initial length and to bend up to 248 degrees depending on the combination of the actuated chambers.**

Keywords—minimally invasive surgery, soft robot, pneumatic actuation, modular robot.

I. Introduction

In the last years surgical procedures have improved with the aim of reducing the invasiveness of traditional medical techniques [1]. Minimally invasive surgery (MIS) has successfully developed with laparoscopic operations, that are based on the access into the abdomen cavity by 4 or 5 trocars. Several dedicated accesses are necessary because traditional tools are elongated but they have a very limited flexibility. In order to reduce the number of the trocars, more tools can be inserted from a single access (single port laparoscopy, SPL), *i.e.* the umbilical one, or through natural entrance as in natural orifices translumenal endoscopic surgery (NOTES), avoiding external visible scars [2]; anyhow these solutions increase the difficulty of the surgical operations [3, 4]. These limitations are at the base of the development of innovative instrumentation with redundant degrees of freedom (DOFs) that ensure more motility and dexterity during insertion, control and operations. Articulated tools are able to reach and work in different districts of the body [5-8] in NOTES or SPL [9-11]. Articulated robots can be used for optimizing surgical operations and also as retraction systems, often necessary in surgery [12]. New technologies allow to design flexible tools which are safer than the traditional ones thanks to their compliance with the tissues [13]. Some examples of flexible manipulators permit to gain a specific configuration when the working site is reached, but generally they lack stability and the contact with the surrounding tissues is not controlled [14].

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The growing interest in the study of biological soft structures, such as the octopus arm and the elephant trunk, allowed the development of new technologies of fabrication and use of new materials to design manipulators with controllable stiffness (from highly compliant to rigid) [15]. The biological inspiration represents an input for the design of more deformable and flexible manipulators, with a redundant number of DOFs and mechanisms to control their stiffness. This leads to the possibility of controlling the interaction with an object and then with a biological tissue. Several solutions have been proposed in order to design a soft multi-articulated robot, and normally actuation systems are based on cables, passive springs [16], pneumatic elements, tendons [17, 18] or smart materials such as shape memory alloys [19]. However, these studies do not resolve the request of combining softness with the generation of large forces.

This work presents the design of a soft manipulator taking inspiration by the octopus biological capabilities, and that is able to elongate, to bend in any direction, to be passively squeezed and to tune its stiffness.

II. Design and Fabrication of the Manipulator

The STIFF-FLOP manipulator is based on a modular architecture that integrates multiple basic units, each characterized by the same capabilities in terms of 3D motion and force generation. The design of the first prototype of the manipulator is shown in Fig. 1.

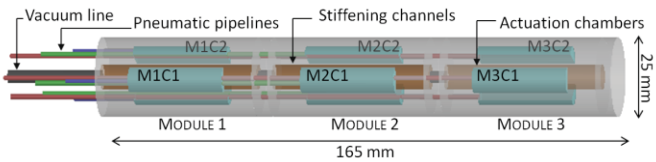

Fig. 1. Overall sketch of the manipulator design.

The overall length is 165 mm and the diameter is 25 mm. These dimensions are not yet compatible with MIS procedures, but at this first stage the research has been more focused on the feasibility and the proof of the modular concept. In the next developmental phase they will be optimized for an application in a real medical scenario. The single module of the arm has a length of 50 mm and consists of an elastomeric cylinder made of Ecoflex 0050 silicone (Smooth-On). Three embedded fluidic chambers are internally arranged at 120 degrees and they actuate the module when inflated and controlled by external valves. The actuation of one single chamber or two chambers simultaneously allows the omni-directional bending, while the inflation of all three chambers elongates the module. A central channel is dedicated to the granular jamming mechanism [21] based on a Latex membrane incorporating granular material. When an external pump activates the vacuum in this channel, the granular matter compacts, thus increasing the internal friction and thus allowing to vary and control the stiffness of the module. A detailed explanation of the single module performance is reported in [22].

The multi-module manipulator integrates three modules, as visible in Fig. 1. Pneumatic actuation supplies the pressure in the modules thanks to nine pipelines (Cole-Parmer). The tubes have an external diameter of 1.5 mm and they are made of soft silicone which maintains flexibility when the manipulator moves. Thanks to their flexibility, it has been possible to insert the tubes inside the actuation chambers with a length longer than the chambers one (Fig. 2) in order to minimize the tubes elongation and guarantee the module functionality.

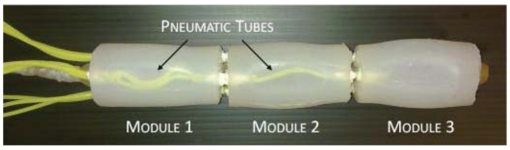

Fig. 2. First phase of three modules integration. The arrangement of the pneumatic tubes inside the actuation chambers is indicated.

Three tubes pressurize Module 1, while the other six pass through the chambers of this module and go to the other modules, thus supplying the pressure in the same way. For this reason, the distal modules are different from the proximal modules, which is the richest in number of passing pipes. The tubes are fixed to the bottom and the top of each module with soft Teflon around thus avoiding possible air leakages also during motion. Three stiffening channels, one for each module, are inserted in the manipulator. They are serially connected; they allow to control the stiffness of the manipulator without selection of the specific module, by activating a certain vacuum level in the vacuum line. The configuration of the tubes for supplying pressure and for activating vacuum makes the manipulator not yet completely modular because every module is bounded to the next one by tubes. Thus in this context the concept of modularity has to be intended from a functional (each module has the same functionalities) rather than structural point of view. In next works, the manipulator will be re-designed in order to pass from the current multi-module structure to a modular one, thus obtaining independent modules easily connectable.

The connection with pneumatic pipelines and the integration of the stiffening channels represent the first phases of fabrication of the manipulator. Then the consecutive modules have to be connected. The junction between two modules is not actuated and it does not include the granular jamming based stiffening channel. It has been designed in order to minimize its non-active effect on the system performance and not to prevail on that. A stiffer material and a small length have been considered to minimize the displacement of this zone when the manipulator works: when in soft state, the rigid junctions do not interfere with the softness of the modules; when in stiff state, the junctions contribute to the stiffness of the entire structure. The silicone Dragon Skin 10 (Smooth-On) has been chosen for this purpose and has been moulded between the modules for a length of 5 mm. The final step of the fabrication consists of the integration of a crimped braided sheath around the manipulator, fixed at the base and the tip. The sheath allows to increase the motion capabilities, thus avoiding the lateral expansion of the fluidic actuators when actuated.

The manipulator represents a closed system where every element is designed inside the basic structure of silicone and protected by it and the external sheath. This configuration guarantees that if an actuation chamber or the stiffening channel breaks, possible dispersion of particles is avoided. However, the low pressures needed for the chambers inflation make the breaking of the chambers a very unlikely event and for the central channel the dispersion of material is almost impossible because a Latex membrane and a thick silicone layer confine the granular matter inside the manipulator.

III. Performance of the Manipulator

For a preliminary characterization of the manipulator, the performance in terms of elongation and bending have been studied. The tip of the arm has been tracked for different cases relative to different values of pressure and different combinations of actuated chambers. The manipulator has been fixed at the base in a configuration similar to a hypothetic medical scenario, in which the base of the arm stops at the abdominal wall and the tip is free to move in the abdomen. As shown in Fig. 3, a 6-DOF tracking probe has been fixed on the tip of the arm and the different positions during the motion have been acquired with the Aurora EM tracking system.

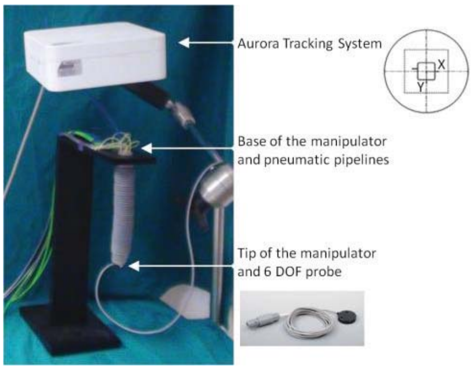

Fig. 3. Set up for the tracking of the tip position during manipulator motion.

For each position 100 samples have been acquired and afterwards elaborated. The tip has been tracked during elongation and bending movements by supplying different values of pressure to the chambers. The range of pressure is 0 – 650 mbar with steps of 50 mbar, that means fourteen tip positions acquired. The pressure 650 mbar represents the maximum actuation pressure for the single module, as discussed in [22].

Considering the different structure of the modules, mainly due to the different number of tubes inside the chambers, the manipulator has been tested by actuating firstly the single modules in order to assess their performance. In the case of elongation, MODULE 1 has been actuated with the fourteen pressures cited before, while the other two modules were passive; the tip position has been acquired. The same tests have been carried out by actuating MODULE 2, and finally MODULE 3. The elongation of the single modules is 29 mm for MODULE 1, 30 mm for MODULE 2 and 31 mm for MODULE 3. The difference between the elongation can be associated to the number of tubes that slightly limit the motion of the proximal module. Moreover, the different values of elongation can be in part due to the fabrication method that is not yet completely repeatable at this level.

Fig. 4 shows the position of the tip during the manipulator elongation, that means all the modules (thus all nine chambers) are actuated in the same instant with the same pressure.

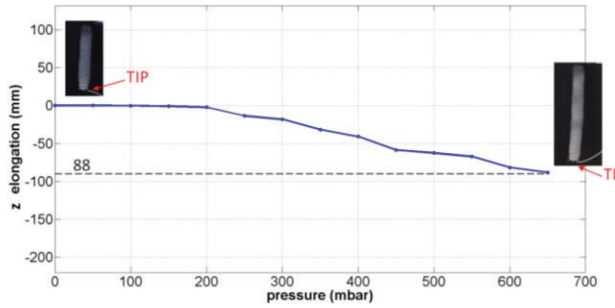

Fig. 4. Elongation of the manipulator when all the modules are simultaneously actuated with the same pressure. In the insets initial and final configurations are shown.

From Fig. 4, it is possible to notice that a significant elongation starts to be visible beyond 200 mbar and it increases up to 650 mbar for a maximum elongation of 88 mm, that means an elongation of 53.3 % and a final length of the manipulator of 253 mm. Looking at the elongation of the single modules, the overall elongation corresponds to their sum. This means that the external sheath, shared between the modules, has a length sufficient to guarantee the right elongation of each module.

Also for the bending, the single modules have been tested in order to identify possible interesting behaviours. Moreover, both the cases of 1-chamber and 2-chamber bending have been tracked. Fig. 5 (Top) shows the tip position when the chambers M1C1, M2C1 and M3C1 (as indicated in Fig. 1) are separately actuated; the same test is carried out in the case of 2-chambers actuation (Fig. 5 Bottom). In the case of 1-chamber bending, the tip is able to describe larger trajectories than the case of 2-chamber bending. This means the possibility to cover different spaces and reach the same position in different ways. Fig. 6 (Top) shows the bending of the manipulator when the chambers M1C1, M2C1 and M3C1 are simultaneously actuated with the same pressures, as discussed before. The fourteen positions of the tip have been acquired to calculate the bending angle for each one. The bending angle is the angle between the orthogonal line to the base and to the tip of the manipulator, as indicated in Fig. 6.

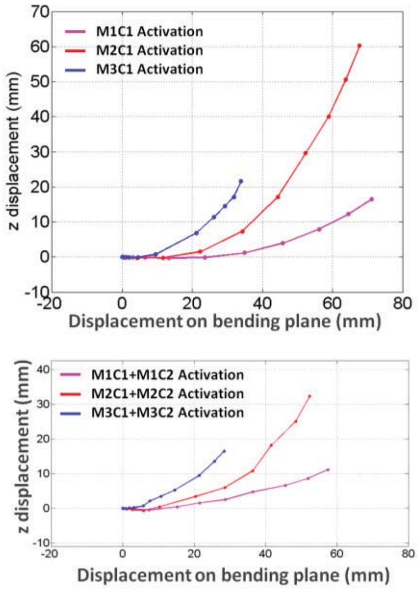

Fig. 5. Tip position during the bending of the single modules. Top: 1-chamber bending. Bottom: 2-chamber bending.

For a pressure of 650 mbar the tip bends of 248 degrees respect to the initial position of the manipulator. In the case of 2-chamber bending the following chambers are actuated: M1C1, M1C2, M2C1, M2C2, M3C1, M3C2. As shown in Fig. 6 (Bottom), the manipulator describes around the half of the trajectory described in 1-chamber bending case and the tip bends of 85 degrees.

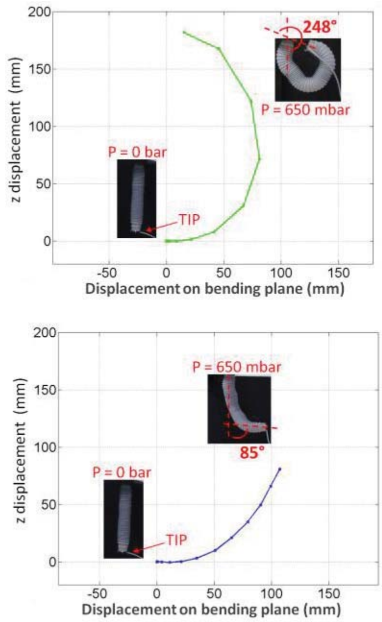

Fig. 6. Top: Tip positions during 1-chamber bending of the manipulator. Bottom: 2-chamber bending of the manipulator. In the insets the initial and the final configurations are reported, respectively for 0 bar and 650 mbar.

The values of length and bending of the manipulator are suitable for an abdominal procedure and compatible with the dimensions of the current tools used in laparoscopy [23]. Due to the placement of the manipulator with the tip going down, as during the entrance of a medical tool in the abdominal cavity, the gravity force influences the behaviour of the manipulator. Theoretically, every module is able of larger bending, but the action of the gravity force limits the trajectory of the tip, as reported in the curves of Fig. 5 and Fig. 6. A theoretical study of the tip position of the manipulator will be carried out, by eliminating the gravity effect and thus obtaining a theoretical model for the bending.

IV. Conclusion

In this work a new manipulator for MIS has been presented. In Section II the design and the fabrication phases have been illustrated. The arm takes advantage of three soft units connected to form a modular structure. This configuration allows to obtain a flexible and redundant manipulator characterized by more dexterity than the traditional tools used in laparoscopic procedures. The manipulator is long 165 mm. It is pneumatically actuated by fluidic chambers, three inside each module. The arrangement of the actuators and an external braided sheath allow to elongate and bend the manipulator in every direction.

A central channel is dedicated to the granular jamming based stiffening mechanism providing a stiffness control of the modules.

Preliminary tests on the performance of the manipulator allowed to study the 3-D motion. The overall elongation of the manipulator, respect to the initial length, is of around 53 % when it is actuated with the maximum pressure. This allows to reach a maximum length of 253 mm that is a tool length compatible for an operation in the abdomen. The different possibilities of bending, due to the several combinations of the chambers actuation, permits to reach different positions. 1-chamber bending allows the tip manipulator to bend of 248 degrees, while in the case of 2-chambers bending the tip describes 85 degrees.

From a first evaluation of the controllable stiffness, the system permits to control the arm up to a Young Modulus of 0.91 MPa [24]. It is worth mentioning that future works will include a more detailed work on the stiffness manipulator when the vacuum in the stiffening channels is applied. Stiffness properties will be studied in combination with the motion in order to assess the potentiality of the manipulator in MIS procedures.

In addition, future works will focus on the miniaturization of the manipulator and the design of a functional tip in order to obtain a device suitable for applications in a real working scenario.

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