Stiffness-controllable octopus-like robot arm for minimally invasive surgery

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***Abstract* – We are presenting a new concept for a robot arm design that can change its structure from complete soft to stiff. The proposed system makes use of the principle of granular jamming: A granule-filled membrane is soft and flexible when the pressure inside the membrane is higher or equal to the outside pressure; however, lowering the pressure inside below the outside pressure jams granules into each other, hence, increasing the stiffness of the structure. Employing this principle, we create low cost, variable stiffness manipulation systems that have great application potential, as for example in the field of minimally invasive surgery. Employing granular jamming, our approach can be used to create controllable-stiffness tools covering the whole spectrum of current surgical manipulation devices – from laparoscopes (straight and rigid) to endoscopes (flexible and soft). Combining the granular jamming manipulation system with end effector tools such as a camera or a gripper, this overall system can fit through a Trocar port and bend around organs in a patient's abdominal cavity providing the surgeon with improved views or a retraction aid.**

Keywords—variable and controllable stiffness, granular jamming, soft robot manipulator, octopus-like, camera/retraction system.

I. INTRODUCTION

Successful and safe laparoscopic and endoscopic surgery is heavily dependent on its vision system, with the primary emphasis on the viewing angle and image stability [1]. Today's laparoscopic instruments are typically long, rigid tubes that have poor accessibility to target areas and often require a second surgeon to aid during the overall procedure. There is a noticeable trend towards natural orifice translumenal endoscopic surgery (NOTES); hence, a number of surgeons prefer flexible endoscopes over the traditional rigid laparoscopes for the operations to be conducted. However, these endoscopes were originally designed for intralumenal use, and tend to be application specific [1]. Thus, there is a technological and clinical need for small, flexible manipulation systems designed for NOTES and other minimally invasive surgical procedures, incorporating retractors, cameras and possibly other elements such as miniaturized force sensors [2].

Our approach – inspired by the biological counterpart: the octopus – aims to bridge these gaps. Our octopus-inspired manipulation device is a 10 mm diameter robot that can alter its body stiffness from being flexible to rigid via granular jamming. Most commonly seen in vacuum packed bags of rice or coffee, granular jamming is a phenomenon where a multitude of particles normally act like a fluid, but lock into a solid-like state when an external stress is applied [3],[4]. Thus, our device is naturally compliant and can be pushed into position by the surgeon's laparoscopic tools, then it can lock its current position when a differential between the internal and external pressure is applied; we achieve this by vacuuming the interior of the robot's membrane.

Fig. 1. An octopus entering a narrow opening.

Fig. 2. A schematic drawing of our low cost, granular jamming-based flexible laparaoscopic camera. Shown here its ability to access difficult areas, while occupying only 4 mm of trocar port space.

This variable stiffness mechanism not only provides the surgeon with a wide viewing angle and accessibility when the robot manipulator is flexible, but also a stable platform once stiffened [5]. Although it requires pneumatic tubing and a tether for video cables and possibly gripper actuation, the entire cable and tube bundle (for our robot that has a camera integrated) is only 4 mm in diameter. The design of the robot allows the manipulator to be deployed into the body cavity, thus only occupying 4 mm of trocar port space after initial insertion, a significant improvement over current endoscopes.

II. METHODOLOGY

The octopus-inspired robot manipulator, seen in Figs. 2 and 3, is 10 mm in diameter, composed of three 65 mm long segments filled with 1.5 mm diameter plastic spherical granules, and followed by a 4 mm tether. The outer membrane is made with a 0.12 mm thick PVC film. The section dividers are ABS plastic and were printed with a rapid prototyping machine. The tip camera is a 10 mm diameter CMOS sensor with a 640x480 resolution at 30 frames per second and was connected to a computer via USB. Vacuum pressure is achieved with a Mastercool 90066-2V-220 pump, and measured by a Honeywell 0-30 PSI absolute pressure sensor.

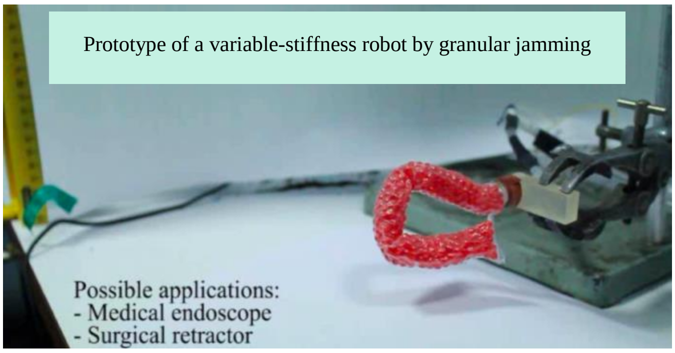

Fig. 3. Here, jamming the granules locks the manipulator into its rigid state, and holding a 180 degree bend. The flexibility and variable stiffness of the camera system allows surgeons to navigate to a area of interest and lock the camera or attached gripper in the position.

III. EXPERIMENTAL RESULTS

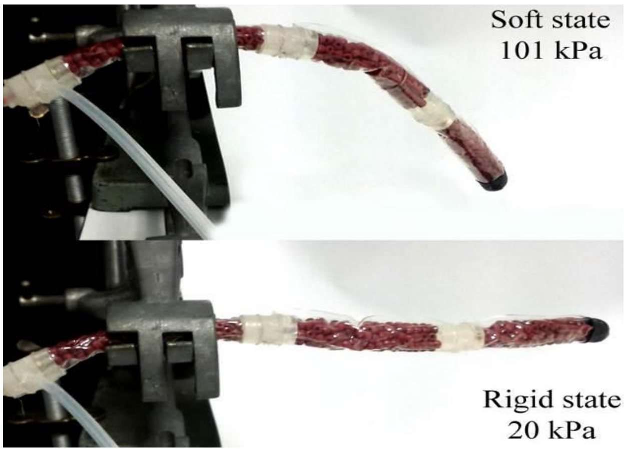

Fig. 4. The granular jamming manipulator bending due to weight when soft (top) vs holding a horizontal position when stiff (bottom).

Other researchers utilizing granular jamming have shown that ground coffee is the ideal granule type for jamming [6]. However, in medical applications, concerns for using organic materials in a surgical system lead to tests to examine if there is a plastic substitute. The synthetic substitute would need to match the stiffness of ground coffee and withstand an autoclave, the most common method of disinfection. We conducted a number of force tests. Our results show that, after deflected, one segment can exhibit 0.20 N of force at 101 kPa (soft state) and 0.42 N at 20 kPa (rigid state). Fig. 4 visually shows what these stiffness values represent: the varied ability to hold the manipulator system in a horizontal position. Thus, the rigidified octopus limb is a stable platform. Bending tests performed evaluating the performance profiles of ground coffee and plastic spheres for granular jamming show that a synthetic substitute achieves improved stiffness.

IV. CONCLUSSIONS

This paper presents a new type of NOTES-orientated robotic manipulation system whose stiffness can be varied, and, is deployable and low cost. The total cost of the camera-equipped manipulator, excluding the vacuum pump, is approximately 20 GBP, 50 times less than traditional laparoscopes. Though some preliminary sterilization tests have been performed for the granules, they have not been done for the manipulator as a unit. Currently, the positioning of the camera can be done by the surgeon’s laparoscopic tools, reducing the need for a “cameraman.”

Future works will involve adding a high definition camera, increasing the stiffness range of the manipulator arm, adding an integrated actuation system, and testing it in-vivo. The integration of gripping mechanisms will be explored.

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