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Highly Articulated Robotic Probe for Minimally Invasive Surgery

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***Abstract* - We have developed a novel highly articulated robotic probe (HARP) that can thread through tightly packed volumes without disturbing the surrounding tissues and organs. We use cardiac surgery as the focal application of this work. As such, we have designed the HARP to enter the pericardial cavity through a subxiphoid port. The surgeon can effectively reach remote intrapericardial locations on the epicardium and deliver therapeutic interventions under direct control. Reducing the overall cross-sectional diameter of the mechanism was the main challenge in the design of this device. Our device differs from others in that we use conventional actuation and still have good maneuverability. We have performed simple proof-of-concept clinical experiments to give preliminary validation of the ideas presented here.**

Index Terms - Snake Robot, Medical Robot, Minimally Invasive Surgery, Cardiac Surgery.

I. INTRODUCTION

Antiseptic techniques, introduced by Lister 150 years ago, have been by far the greatest single improvement in the art and science of surgery. This has enabled the core surgical task of “cutting and sewing” with hand instruments, allowing direct visualization and contact. The next great improvement, which will have a far greater impact than antiseptic techniques, has begun. This improvement lies in minimally invasive surgical approaches where a small incision is made and the surgeon performs the operation through specialized tools inserted through the incision. Many areas of surgery have been revolutionized by the development of minimally invasive surgical procedures developed after the introduction of fiber optic technology (i.e. endoscopy, laparoscopy, etc.)

Conventional minimally invasive surgical devices are either 1) rigid and straight, or 2) flexible and buckle easily. This paper describes our initial efforts in developing a new medical device which has the best of both worlds; it is both rigid and flexible and therefore well suited to minimally invasive surgery. The mechanism described in this paper can be viewed as a snake robot, but we prefer to call it a highly articulated robotic probe or HARP, for short.

We have chosen the cardiac domain as a focal application because the challenges faced in cardiac surgery are representative of challenges faced in other procedures. Moreover, according to a recent Gallup Poll, heart disease and heart attack are ranked second, after cancer, as a major health concern for Americans, preceding other diseases such as arthritis, stroke, high blood pressure and diabetes. The Center for Disease Control and Prevention concluded in their 1996 report that cardiovascular diseases (principally ischemic heart disease and stroke) are the nation’s most common cause of death among both men and women of all racial and ethnic groups. This trend is supported by the 2004 annual statistical report of the American Heart Association which indicates that since 1900 cardiovascular disease has been the number one killer in the United States every year but 1918.

Cardiac surgery is different from other surgical procedures because the large sternotomy incision required to access the heart requires general endotracheal anesthesia. The heart-lung machine that is required for open-heart surgery (e.g. valve repair) adds further morbidity. If for that reason only, performing an epicardial intervention in a less invasive manner will dramatically improve recovery and decrease risks involved with the current procedures.

The HARP mechanism, described in this paper, differs from previous devices in its ability to form a curve in a three-dimensional space with only six actuators. We present an overview of existing medical devices, show the mechanical design of the HARP and report experiments on pig models.

II. OVERVIEW

A. *Minimally Invasive Surgery*

It is almost self-evident that minimally invasive procedures have clear clinical benefits to patients when compared to “open” procedures. By virtue of the minimal invasion, performing any procedure less invasively results in less soft tissue disruption, with the effects of reduced pain, faster healing and better recovery. It has already been documented that less invasive procedures which include smaller incisions and fewer injuries to major blood vessels and nerves improve patient care [1]. As a byproduct of minimally invasive techniques, patients require shorter hospital stays and return faster to normal activity [2].

B. *Minimally Invasive Cardiac Surgery*

We believe that the HARP will be ideally suited for minimally invasive cardiac surgery (MICS). The HARP can enter the pericardial cavity through a subxiphoid port, reaching remote intrapericardial locations on the epicardium without causing hemodynamic and electrophysiologic interference while delivering therapeutic interventions under the direct control of the surgeon (Fig. 1). Some of these

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potential intrapericardial therapies include: cell transplantation by intramyocardial injection, epicardial ablation, and epicardial lead placement for resynchronization.

The subxiphoid route, depicted in Fig. 2, is an ideal point of entry for cardiac procedures because its use avoids the need for a large sternotomy incision. Zenati et al. pioneered this approach for epicardial left heart pacing lead implantation for resynchronization [3, 4]. The subxiphoid videopericardioscopy (SVP) device (Guidant Corporation, Santa Clara, California) is the only dedicated technology available for endoscopic video exploration of the pericardial cavity (Fig. 2). One major problem associated with the present configuration of the SVP device is its rigidity and the significant potential that the compression of the beating heart will trigger a life-threatening arrhythmia. Most of the anatomical targets for videopericardioscopy are located in remote areas of the pericardium, away from the entry point in the pericardium below the xiphoid. Our 12mm in diameter HARP can get to those hard to reach anatomical targets by using its high redundancy and maneuverability while minimally interacting with the environment along its path.

C. *Related Work in Medical Devices*

Endoscopic instruments are the main tools used today in minimally invasive surgery (MIS). A typical endoscope consists of a long 10mm in diameter tube with a length of 70 to 180 mm. Although these devices have a steerable tip which allows them to be directed inside the body, current endoscopic tools cannot maneuver in very small and geometrically complex spaces. To overcome this problem numerous works have been presented on active catheters and endoscopes which try to increase their maneuverability. Much of these works have focused on developing a new form of actuation, such as shape memory allows (SMA) [5, 6] and electric polymer artificial muscles (EPAM) [7, 8].

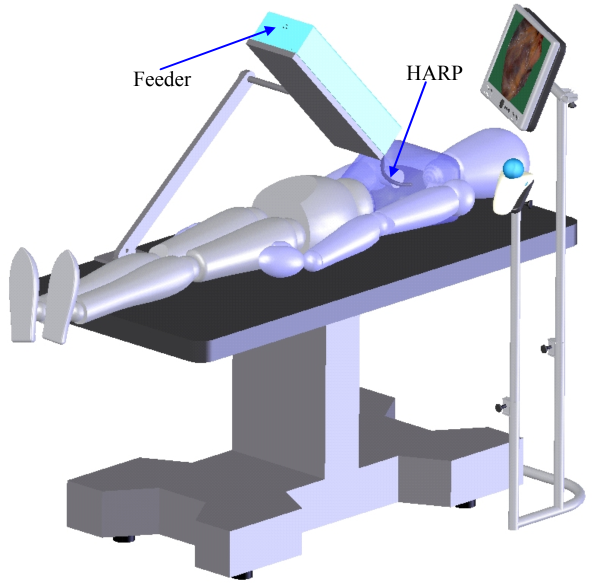

Fig. 1: HARP is shown as a snake-like mechanism protruding from a current feeder mechanism attached to the operating table.

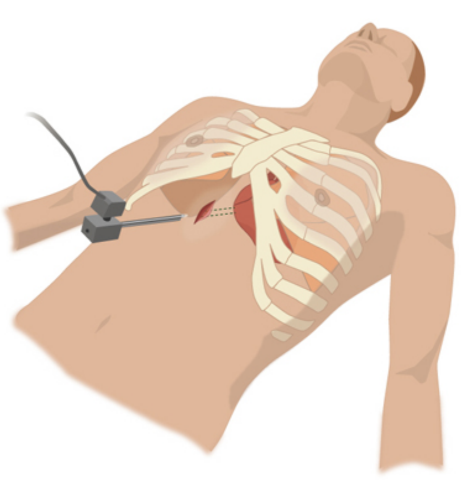

Fig. 2: The subxiphoid route opening. This figure depicts the straight and rigid videopericardioscopy device (Guidant Corporation, Santa Clara, California).

The Laboratoire de Robotique de Paris (LRP) developed an 8mm in diameter snake-like mechanism which is formed by a sequence of segments articulated to by SMA actuated pin joints [9]. Hirose [10] also used an SMA spring and wire actuation to make a small surgical device; the novelty of his mechanism is that it overcomes hysteresis commonly found in SMA's. In [11] the researchers developed a 2.8mm in diameter active catheter based on silicon micromachining. This multilane manipulator is connected by joints made of SMA, fixed at equilateral triangular locations to allow bending in several directions. Other endoscopic, SMA and Piezoelectric based, tools are presented in [12-16].

Although SMA's offer a compact alternative to conventional actuators, virtually all SMA tools have relatively low stiffness, and require high activation voltage. This high activation voltage then makes removing heat difficult

A different activation concept is presented in [17] and [18]. In these works the authors presented snake-like tools using super-elastic NiTi which has higher stiffness than other SMAs but the heating problem and complexity of multiple degrees of freedom (DOF) is still relevant, resulting in limited DOF mechanisms.

Lately there has been an increase interest in Electrostrictive polymer artificial muscle (EPAM) for medical applications [19]. An EPAM based snake-like endoscopic robot was developed at Stanford Research Institute (SRI). The device is composed of several spherical joints attached serially around a concentric spine [7]. Researchers at Pennsylvania State university [8] have also developed a snake-like manipulator using EPAM. Their special design of the actuator allows control of the curvature.

Another popular actuation scheme is wire actuation, such as the arthroscope tool developed at the Santa Anna laboratory in Pisa, Italy, [20]. The 25-mm long distal section of the arthroscope has a 1-DOF with an angle range of 0° to 110°. Overall accuracy of the device is 2.3mm.

Perhaps the biggest drawback to wire actuation, SMA, and EPAM actuators is that they do not have the strength to "hold" the device in three dimensions. This means that they cannot form a true three-dimensional curve. These devices, for which they were most likely originally designed, can only operate inside a luminal or tube-like environment.

III. HARP DESIGN AND OPERATION

A prototype of the highly articulated robot for minimally invasive surgery has been built and tested in our lab. The current prototype is 12mm in diameter, and 300mm in length. The choice of 12mm is based on available ports. With the feeder mechanism, described below, the overall dimensions of the mechanism are approximately 500 mm length, 170 mm width, 100 mm height (Fig. 3).

Four cables actuate the probe. The source of actuation is off-board which means that no electric power, heat dissipation, etc. occurs inside of the HARP, and hence inside the body, when the HARP is inserted into a patient.

Visual feedback from the distal link is relayed by a 2mm diameter fiber optic endoscope attached to the outer snake, and displayed on a monitor.

A. Design Concept

The HARP design consists of two concentric tubes. Since these tubes resemble snakes, we refer to these tubes as "snakes." Each snake can alternate between being rigid or limp. In rigid mode, the mechanism is just that – rigid. In limp mode, the mechanism is highly flexible and thus either assumes the shape of its surroundings or can be reshaped. The HARP follows an arbitrary three-dimensional curve by alternating the rigidity/limpness of the outer and inner snakes. Assume we start with both inner and outer snakes as rigid. The outer snake is made limp and advances forward one link. Even though the outer snake is limp, it maintains most of its shape because the inner snake is rigid. However, since the outer snake is indeed limp, it can "steer" its head, the link which was advanced forward. Now, the outer snake is made rigid, the inner snake is made limp, the inner snake advances until it "catches up" to the outer snake, the inner snake is make rigid, and the procedure repeats.

Both inner and outer snakes consist of rigid cylindrical links connected by a type of spherical joint which can rotate ±15° range in both degrees of freedom. The links are strung together by cables, three for the outer snake and one for the inner snake. These three cables are 120° apart, making it possible to steer in any direction, as well as selecting between rigid and limp modes. When the cables are pulled towards the back of the mechanism, the links are pulled towards each other increasing friction between the links eventually causing the outer snake to become rigid; when they are relaxed, the outer snake becomes limp.

The inner snake resembles the outer snake. However, in the current design of the snake, the inner snake has only one concentric cable which stiffens the inner snake when pulled upon it, and is not steerable. The cross section of the two concentric snakes is presented in Fig. 4.

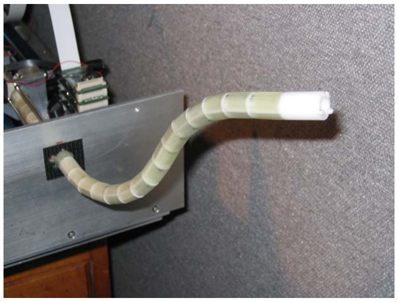

Fig. 3: HARP prototype

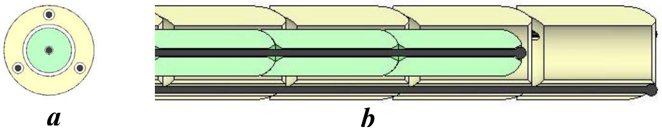

Fig. 4: Side (a) and front (b) cross sectional view of the two concentric snakes

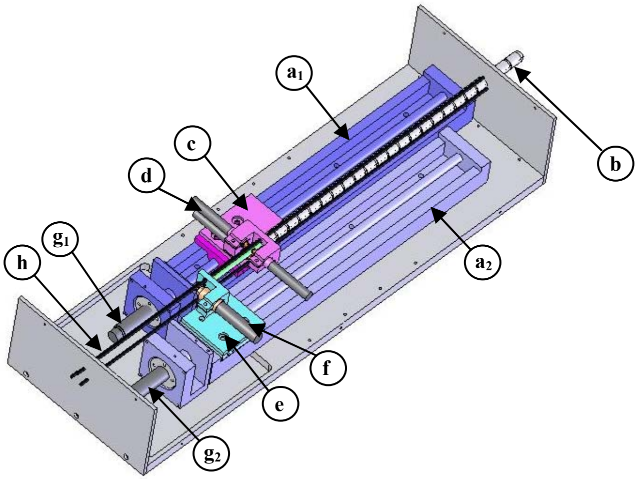

Fig. 5: HARP mechanism assembly

B. Feeder Design

The feeding mechanism inserts the HARP into a region of interest. Referring to Fig. 5, the feeder has two movable carriers. A first carrier (marked c) drives the outer snake and a second carrier (e) drives the inner snake. Each carrier, and hence the inner and outer snakes, are driven independently by separate linear motion systems (a_1, a_2). Each of the carriers (c and e) transports motors necessary for controlling the cables of the inner snake and outer snake. The outer snake carrier (c) transports three motors (d) which control the tension on the cables of the outer snake. The second carrier (e) transports a motor (f) for controlling the tension on the cable of the inner snake.

C. Gait Sequence

In this section, we describe in more detail a gait sequence which enables the HARP to preserve its configuration while propagating forward.

- The inner snake is stiff while the outer snake is limp (Fig. 6a).
- The feeder pushes the outer snake until its distal link is positioned one link ahead of the end of the inner snake (Fig. 6a).
- The orientation of the outer link is determined, either by a computer program, a user joystick interface, or autonomous intelligent algorithms. This determines the relative tensions on the three outer cables which in turn orients the distal link of the outer mechanism (Fig. 6b).
- The three cables are pulled with identical force in order to stiffen the outer snake in its configuration (Fig. 6b).
- The inner mechanism is made limp by releasing the pulling force of the inner concentric cable, and the feeder pushes the inner snake until its distal end is approximately flush with the end of the outer mechanism (Fig. 6c).
- The inner snake is stiffened by pulling the inner cable. This preserves the configuration of the outer snake so the process can repeat allowing the outer mechanism to advance while preserving the rest of its shape (Fig. 6c).
- The outer snake is made limp and is pushed one link forward (Fig. 6d).
- The process repeats (Fig. 6e,f).

D. Design Considerations

1) *Applied Loads:* To determine the torques required from the motors, as well as the material of the HARP itself, we consider an extreme or worst-case configuration for the HARP where the actuators have to exert the most torque. Such an extreme configuration occurs when the device is stretched out in a cantilevered position, the outer snake is limp, and the inner snake supports its own weight as well as the weight of the outer snake (Fig. 7a). To estimate the axial force needed to be applied by the cable of the inner snake to support this configuration we generated a simplified model of this extreme configuration. For this simplified model we approximated the system parameters: outer snake link weight as 1.5 grams, inner snake link weight as 0.5 grams, number of links in each snake as 17, total weight as 34 grams, total length of the HARP as 300 mm, outer snake outer diameter as 12 mm, and inner snake outer diameter as 6 mm.

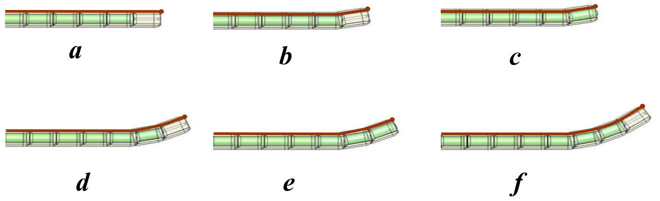

Fig. 6: Typical gait sequence of the mechanism

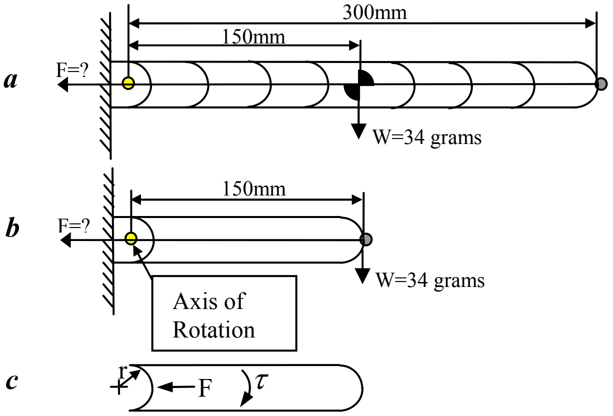

Fig. 7: Schematic of extreme cantilever configuration a. Extreme configuration b. Simplified model c. Free body diagram of extreme configuration

The weight of the HARP is simplified to a point mass at the center of gravity of the HARP. The largest torque is exerted on the area between the two proximal links of the snake. Therefore we simplified the model to include only one long link that is in contact with the proximal link (Fig. 7b). The cable of the inner snake is applied with an axial force, *F*, at the center of the snake (Fig. 7b). A free body diagram of the simplified model is shown in Fig. 7c.

The approximated relation between the force *F* and the torque τ applied on a spherical surface with radius *r* and friction coefficient μ is given in Equation (1).

$$\tau = \mu F r \Rightarrow F = \frac{\tau}{\mu \cdot r} = \frac{50\ N \cdot mm}{\mu \cdot 3mm} \approx \frac{17N}{\mu} \tag{1}$$

In order to estimate the torque required from the motor in order to pull the cables we use the relationship between the motor torque (τ_{motor}), the radius of the pulley (r_p), and the pulling force on the cable (F):

$$\tau_{motor} = F\ r_p \quad \Leftrightarrow \quad F = \frac{\tau_{motor}}{r_p} \tag{2}$$

As observed in (2), in order to output a higher force per given motor torque, a small radius of the pulley is required. We used a machined 10-24 screw as the pulley, which has approximately a 2mm radius. In the current design of the HARP the outer snake, when in a stiff mode, is able to withstand loads of about 1-5N (depending on the direction of the load and the configuration of the mechanism).

2) *Choice of Material:* It is clear from (1) that the friction coefficient is crucial. When the friction between links is low, the pulling force that is needed to withstand the mechanism's own weight is enormous. For this reason the material selection of the links is a crucial factor.

Three different materials were tested: Aluminum, and two types of high pressure laminated glass reinforced epoxy materials. The aluminum and one of the epoxy materials had a friction coefficient of approximately 0.2-0.3, but after a few minutes of being rotated under load, the contact surface was polished and smoothed out, and the friction coefficient dropped dramatically making these materials unfit for our design. The second choice of epoxy material, however, has a very high friction coefficient (approximately 0.5) and was durable to polishing. This material is also MRI safe.

With this material, it was possible to use a reasonable cable pulling force (approximately 25 lbf) to hold the weight of the whole snake in the cantilevered extreme configuration, as described above. Furthermore, this pulling force was sufficient to withstand additional torques caused by steering the distal link of the outer-snake.

3) *Choice of Cables:* An implication of using the material described previously is the need for a non-abrasive cable capable of achieving a tight radius of curvature, on the order of 2mm as required by the pulley from (2). Therefore we used a polyethylene cable, with 0.030” diameter, a breaking force of 150 lbf, and a low stretch (about 3%).

IV. PRELIMINARY EXPERIMENTS

The HARP prototype was tested in three different healthy and large (35-45 kg) pigs. The experiment protocol was approved by the Institutional Animal Care and Use Committee (IACUC) of the University of Pittsburgh. We performed preclinical feasibility testing of the HARP prototype in the intrapericardial environment and in abdominal laparoscopy.

The thoracic experiments were performed in the anesthetized animals following a median sternotomy (see Fig. 8). A small 15mm opening was created on the pericardium at the junction with the diaphragm; through this opening the HARP was remotely guided to slide between the pericardium and the anterior wall of the right ventricle on the beating heart. The HARP was advanced to the root of the aorta and was then withdrawn out of the pericardium (Fig. 9). This task was repeated several times to test deployment speed and amount of resistance offered by the motion of the beating heart and from the intact pericardium.

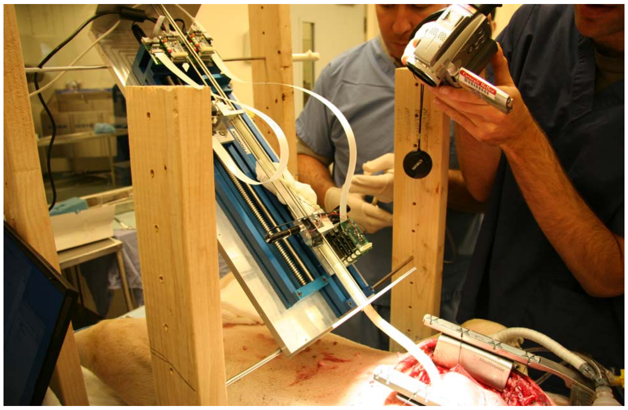

Fig. 8: Preliminary HARP setup where the fixturing device is rigidly attached to the operating table and the HARP itself is being inserted into the thoracic cavity of a pig.

After the completion of the experiment, the pericardium was opened wide and absence of any gross epicardial damage to the heart was confirmed by visual inspection. No adverse hemodynamic or electrocardiographic interference induced by the motion of the HARP was detected.

The abdominal laparoscopic experiment was performed using a conventional 15mm endoscopic port positioned in the right lower abdominal quadrant (Ethicon Endosurgery, Somerville, NJ). Visualization of the HARP was provided by a laparoscope positioned through an additional abdominal port in the left lower quadrant. Insufflation of the abdominal cavity with CO_2 was performed. The HARP was successfully advanced using remote tele-manipulation through the port and into the abdominal cavity (Fig. 10). The HARP was advanced towards the right kidney region after retraction of the small bowel (Figs. 11-13). This experiment was repeated several times using different trajectories. No damage to the intra-abdominal structures was realized.

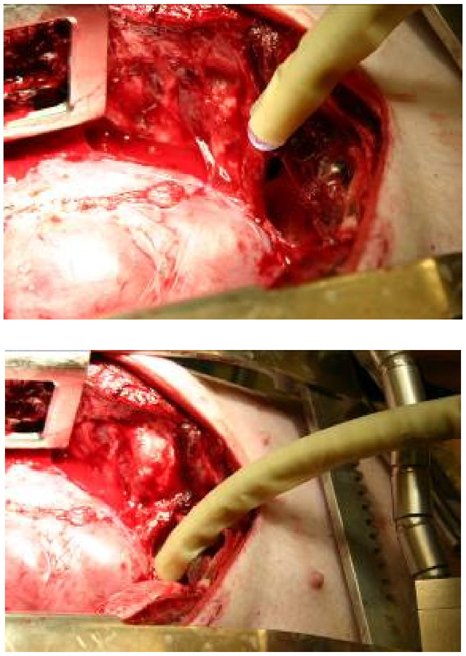

Fig. 9: HARP probe inserted into a live pig

Fig. 10: HARP inserted to the abdominal cavity

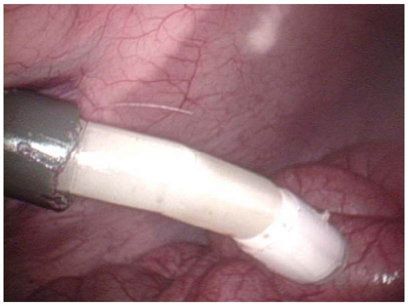

Fig. 11: HARP entering the the abdominal cavity

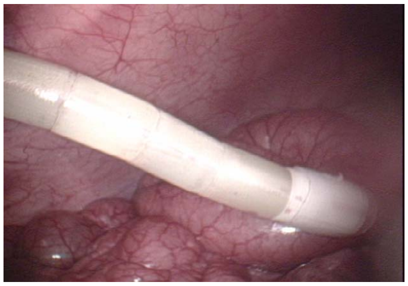

Fig. 12: HARP continuing into the abdominal cavity

Fig. 13: HARP reaching the kidney by passing the intestine

IV. CONCLUSION AND DISCUSSION

In this paper we presented a new medical device that will be useful for minimally invasive surgery. This highly articulated robotic probe (HARP) device has already been built in a 12mm cross-sectional diameter prototype. In addition to its small size, the main advantage of the HARP device is its ability to follow a curve in a three-dimensional space. It can do this because it is able to "preserve" its previous configuration. Another nice feature of the HARP is that it has no mechanical actuation on board the device; all of the actuation is achieved through cables connected to actuators located in the feeder.

The HARP mechanism described in this paper is the first prototype and several more iterations are needed to solve some limitations. As discussed in the paper, the interplay of adjacent links, in particular the friction between them is critical. Hence, we must consider different materials.

We are in the process of designing and building the next prototype which has better curvature capabilities and has a better visual feedback. Thus, a more serious integration effort must be undertaken. The next step is to include end-effectors or tools into the device. Already, we have performed some preliminary experiments where we reached a target in the epicardium, locked the outer snake, removed the inner snake and inserted a colonoscope forceps through the HARP to remove some tissue.

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