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# Toward a Hybrid Snake Robot for Single-Port Surgery

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***Abstract*— We propose a new snake-like robot for use in single-port minimally invasive surgery. The snake robot is made of a concentric tube robot and a highly articulated robotic probe. The probe operates as a stiff shield for the concentric tube robot. Consequently, the snake robot provides simultaneously high tip stiffness and dexterity that cannot be obtained by the single use of any of two robots. A critical design challenge is achieving a small radius of curvature for the hybrid snake. A mechanic model is presented for computing the minimum achievable radius of curvature for the hybrid snake. Experiments validate the mechanic model.**

## I. INTRODUCTION

There is broad consensus that the future of minimally invasive surgery lies in single port access surgery [1]. In single port surgery, the targeted surgical sites are accessed through only one port of entry such as natural orifices or subxiphoid [11]. Single port surgery leaves little or no scarring and may reduce complications that occur after traditional open and even traditional endoscopic multi-port surgery.

Current surgical instruments for single port access surgery include flexible hand-held surgical tools [9], flexible catheters, and flexible robotic instruments [6]. These instruments have been generally used for tissue ablation and excluding organ parts. There are several complex tissue manipulation tasks (e.g. deforming, dissecting, and retracting) that cannot be performed with these instruments. These complex tissue manipulation tasks can be potentially performed with robotic instruments that simultaneously provide tip dexterity and tip stiffness [10]. Snake- like robots with high tip dexterity and stiffness can assist surgeons to operate in confined spaces in similar way that dexterous rigid robots assist them to perform multi-port surgery.

Two types of snake-like robots have been already proposed for single port surgery: serpentine robots and continuum robots. Surgical continuum robots include steerable catheters [6], super elastic backbone robots [3] and concentric tube robots [5], [4]. Surgical serpentine robots are made of a series of rigid links that are actuated either by conventional motors [2] or by shape memory actuators [8]. Unfortunately, both categories of snake robots come with their own tradeoff's: They either exhibit high stiffness and low dexterity, such as the serpentine robots, or exhibit high dexterity and low stiffness, such as the continuum robots.

In this paper, we introduce a hybrid snake robot that can provide simultaneously high tip stiffness and dexterity. The hybrid snake robot is made of a highly articulated robotic probe [2] and a concentric tube robot [4]. We then calculate the minimum radius of curvature of the hybrid snake robot that can be obtained for the cable tension of its probe.

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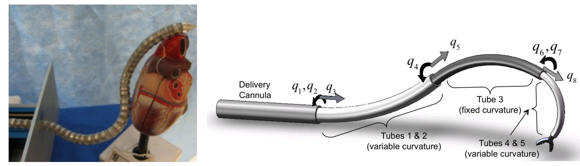


Fig. 1. (left) A highly articulated robotic probe made of several rigid tubular links [2] and (right) A concentric tube robot constructed from several superelastic Ni-Ti tubes [4]

Figure 1 (left) shows a highly articulated robotic probe [2]. The probe is made of two mechanisms: an inner mechanism and an outer mechanism. Each mechanism composed of several rigid tubular links connected with cables. When the cables of a mechanism are tightened, the mechanism becomes stiff. The probe can follow a tortuous path in three dimensions with making one mechanism stiff and extending the other mechanism, which is limp, along the stiff one.

Figure 1 (right) shows a concentric tube robot [4] which is constructed from telescopically extending concentrically combined precurved superelastic tubes. The robot's shape and tip location are controlled by rotating and translating the tubes at their proximal ends. The robotic probe can take any shape but it has a limited tip dexterity. The concentric tube robot is flexible by design but can provide tip dexterity.

## II. HYBRID SNAKE DESIGN

The hybrid snake robot is composed of a robotic probe and a set of pre-curved Ni-Ti tubes as shown in Figure 2. The tubes are mounted in the space between the inner mechanism and the outer mechanism of the probe inside a narrow channel.

### *A. Tubes of Hybrid Snake*

Two pre-curved tubes of the same length, initial curve, and bending stiffness are used for the hybrid snake (Figure 3). The tubes are composed of two constant curvature segments: 1) a long straight segment which is longer than the length of the robotic probe and 2) a short curved section which is long enough to provide sufficient tip displacement for the intended task. The outer and inner diameters of both tubes are selected such that they can be inserted inside each other and the combination can be inserted inside the port of the robotic probe. We refer to the combination of two tubes as combined tube.

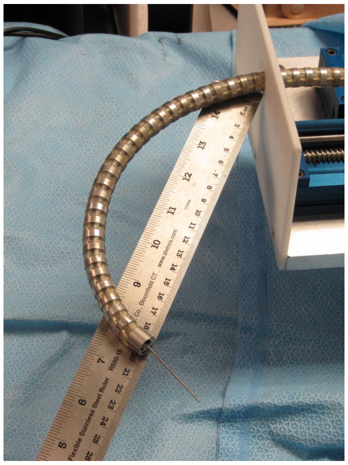

Fig. 2. Hybrid snake robot Concept

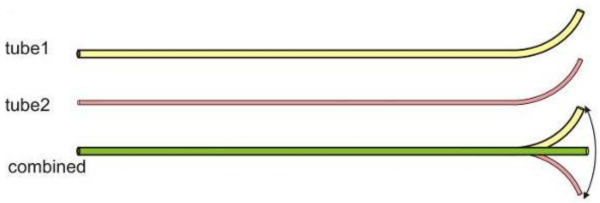


Fig. 3. Tubes of the hybrid snake

By rotating two tubes with respect to each other, the curvature of the curved segment of the combined tube varies from zero (straight configuration) to a maximum curvature. When the combined tube is inserted into the robotic probe, the straight portion takes the shape of the robotic probe. The combined tube can also extend and rotate inside the robotic probe and the orientation of its distal portion can be changed by the last link of the robotic probe.

Two or three concentric tubes can generally provide tip dexterity required for many intended surgical tasks. A hybrid snake requires less tubes than a concentric tube robot for reaching the same curved confined spaces and providing the same level of tip dexterity.

### B. Kinematic Model

The kinematic model of the hybrid snake is decomposed into the product of the kinematic models of the probe and the concentric tube robot. The configuration of the tip of hybrid snake relative to a reference frame, can be written as the product of two transformations

$$g_h = g_p g_{hp} \tag{1}$$

where $g_h$ is a rigid body transformation of the tip of the hybrid snake, $g_p$ is the transformation of the tip of the probe, and $g_{hp}$ is the transformation of the tip of the concentric tubes in respect to the tip of the probe. $g_p$ depends on all joint angles of the probe. $g_{hp}$ depends on rotational angles and insertion length of the tubes. The kinematic model of the hybrid snake can be obtained by combining available kinematics models for concentric tube robots [4] and the articulated probe [2] as given in (1).

### C. Minimum Radius of Curvature

There is no critical problem with creating concentric tubes with a small radius of curvature. Ni-Ti material (Ni-Ti Tubes Inc, Fremont, CA) has recoverable strains of more than 8 percent [5] . With this recoverable strain, a NI-TI tube of 2 mm diameter can take the minimum radius of curvature of 1.25cm. This radius is small enough for many intended surgical applications.

However, building a hybrid snake with a small radius of curvature is challenging. The limited strength of the probe limits the curvature of the hybrid snake. When concentric tubes are mounted into a probe, each mechanism of the probe should be strong enough to curve the tubes.

Here, we calculate the total cable tension of a mechanism required to keep a tube or tubes on a small radius of curvature. We first make these assumptions: 1- the weight of the Ni-Ti tubes and the mechanism are ignorable, 2- the concentric tubes pass along the center line of each mechanism 3- there is no clearance between the tubes and the channel of the mechanism that houses the tubes.

Each probe mechanism can sustain a limited torque [2] at its joints. The maximum torque that a joint of the mechanism can sustain is [2]

$$\tau_{max} = \mu r F_c \tag{2}$$

where $\mu$ is the friction constant between joint surfaces, $F_c$ is the cable tension, and $r$ is the radius of the joint.

Now, consider a section of the mechanism that extends from $s = a$ to $s = L$ (Figure 4). When the mechanism deforms the tubes from the initial curvature $\hat{u}(s)$ to a new curvature $u(s)$, a bending moment, $m(s)$, is generated. Assuming linear elastic behavior for the tubes, the bending moment at point $a$ along the tubes is given as [7]

$$m(a) = K(a)\,(u(a) - \hat{u}(a)) \tag{3}$$

where $K(a)$ is the frame-invariant stiffness tensor. For the tubes, $K(a)$ is given by

$$\begin{aligned} K(a) &= \begin{bmatrix} k_x(a) & 0 & 0 \\ 0 & k_y(a) & 0 \\ 0 & 0 & k_z(a) \end{bmatrix} \\ &= \begin{bmatrix} E_x(a)I_x(a) & 0 & 0 \\ 0 & E_y(a)I_y(a) & 0 \\ 0 & 0 & J_p(a)G(a) \end{bmatrix} \end{aligned} \tag{4}$$

where $E_x(a)$, $E_y(a)$ are moduli of elasticity, $I_x(a)$ and $I_y(a)$ are area moments of inertia, $J_p(a)$ is the polar moment of inertia and $G(a)$ is the shear modulus.

As shown in Figure 4, the concentric tubes apply a combination of distributed forces $\eta(s)$ and moments $\phi(s)$ along their length to the mechanism. The bending moment $m(a)$ at point $a$ of the tubes is defined as

$$m(a) = \int_a^l (\eta(s) \times r(s) + \phi(s))ds \tag{5}$$

where $r(s)$ is a vector that defines the point $s$ of the tubes in a local frame at point $a$. This bending moment is equal to the torque applied to the mechanism at point $a$ due to the forces $\eta(s)$ and moments $\phi(s)$.

Now we consider a tube (or tubes) with a constant curvature $1/R$ and curvature vector $u(s) = [1/R\ 0\ 0]$. The bending moment for the tube is calculated by (3) and (4) as

$$m(a) = [EI/R\ 0\ 0] \tag{6}$$

Assume $a$ is the center of a spherical joint of the mechanism, then this joint can hold the tubes at the radius of curvature $R$ if

$$\tau_{max} \geq m_1(a) = \frac{EI}{R} \tag{7}$$

The minimum radius of curvature that the mechanism can create is then obtained as

$$1/R_{min} = \frac{\tau_{max}}{EI} = \frac{\mu r}{EI} F_c \tag{8}$$

This shows a linear relation between the maximum curvature of the mechanism and the applied cable tension.

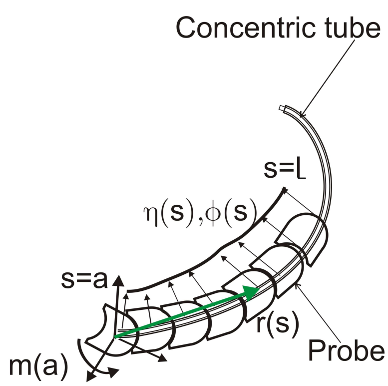


Fig. 4. Bending moment between NI-Ti tubes and a probe mechanism

## III. Experimental Validation

A series of experiments were performed to validate the models (2) and (8) .

### A. Setup

Seven tubular links of the inner mechanism of the robotic probe were used to perform the experiments(Figure 5). The tubular links were connected with a cable that goes through the center of the links. The mechanism is mounted on a piece of wood and gravity loading is used to create cable tension $F_c$. The total length of the mechanism is 4cm.

### B. Experiment I

The first experiment is to validate the linear relation between the maximum joint torque and the cable tension (2). No Ni-Ti Tube was used during this test. The mechanism was set to a straight configuration and gravity loading was used. For each load, a force was applied to the tip of the mechanism perpendicular to straight configuration of the

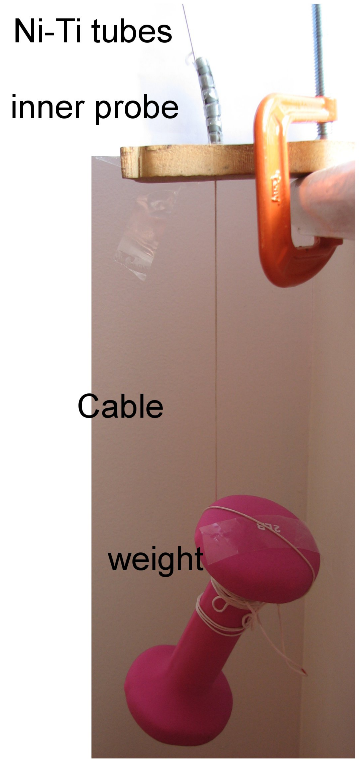


Fig. 5. Setup to measure the maximum joint torque and the minimum achievable radius of curvature of hybrid snake

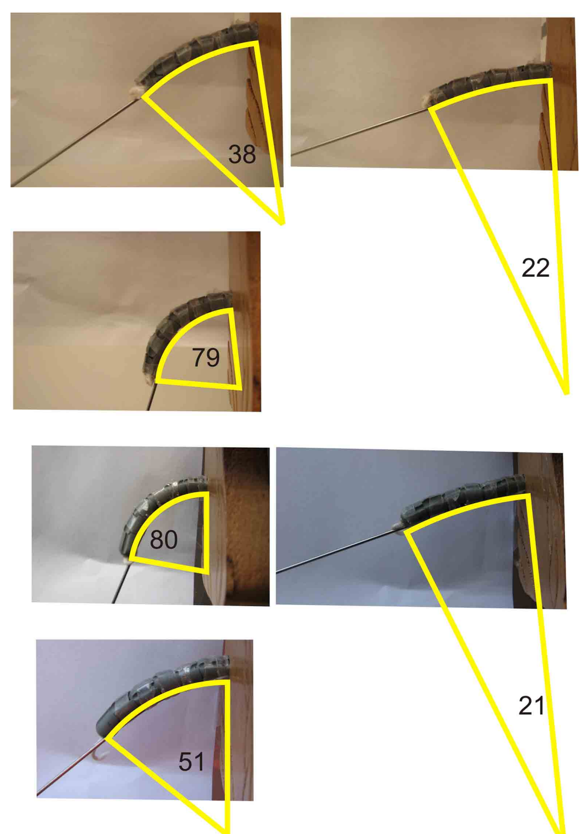


Fig. 6. Measured Curvatures. Three top pictures are for tube 1 and tensions of 9.16 N, 18.32N, and 36.64 N. Three bottom pictures are for the combination of tubes 1 and 2 and tensions of 18.32 N, 45.8N, and 73.28 N.

mechanism until the first proximal joint of the mechanism started to move. The applied force is measured by a 22-N tension/compression load cell (Sensotec model 31). The applied torque to the joint is the product of measured normal force and the length of the mechanism.

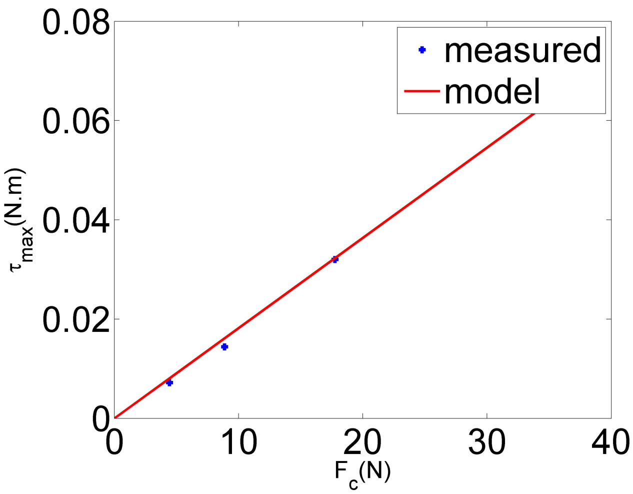


Fig. 7. Joint torque vs. cable tension

Figure 7 compares the measurement results and the outputs of the the model (2) obtained for $r = 3mm$ and $\mu = 0.42$. The model accurately predicts the measurement results.

### C. Experiment II

The second experiment is to validate the relation between the minimum radius of curvature and the cable tension (2). Each link of the mechanism has three grooves. The tubes were located inside one of the grooves. Then, we covered these grooves with a piece of tape such that the Ni-Ti Tubes would not slip out of the grooves. During these experiments, we used two Ni-Ti tubes with these stiffness tube1: 0.00137 $N.m^2$ and tube2: 0.00116$N.m^2$. During each test, the mechanism was first set to a straight configuration and gravity loading was used. For each load, then, the mechanism was bent manually to a maximum curvature allowable by the applied cable tension. For each load, the final shape of the mechanism was captured by a camera (Figure 6). A circle was fitted to the picture of the mechanism in each test and the angle of the portion of the circle in contact with the mechanism was measured. The radius of the curvature of each mechanism is the length of the mechanism divided by the measured angle.

Figure 8 compares the measurement results and the outputs of the model (8) obtained for $r = 3mm$ and $\mu = 0.42$ both tube 1 and the combination of tube 1 and 2. The model predication of the desired cable tensions is sufficiency accurate.

## IV. Conclusion

We introduced a hybrid snake robot that provides both tip dexterity and stiffness required for many surgical tasks. The

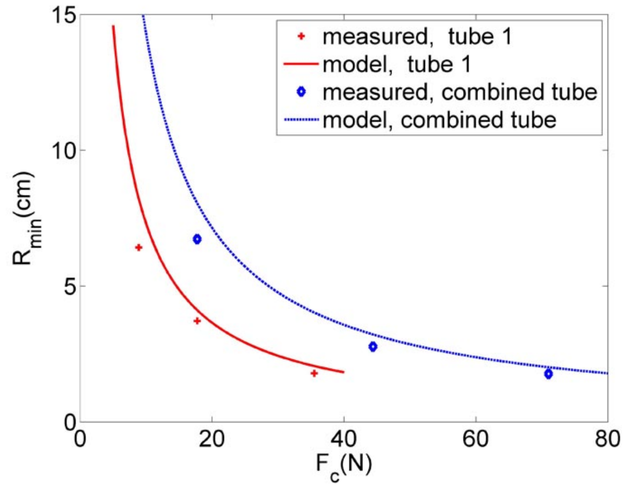


Fig. 8. Minimum radius of curvature vs cable tension for tube 1 and combination of tube one and two

hybrid snake should be strong enough to achieve the required radius of the curvature. We obtained a mechanic model that relates the maximum achievable curvature of a hybrid snake to the tension of its cables. The motors of the snake robot and its cables should be designed such that they can provide required tension. The future work includes the development of the hybrid snake and performing tissue manipulation tests.

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