Fruit harvesting continuum manipulator inspired by elephant trunk

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Abstract: By combining the investigation of the biomechanics and behavior of elephant trunk in the performance of a wide range of dexterous manipulations, a novel approach in the design and kinematics modeling of a fruit harvesting continuum manipulator was proposed. By comparing the structure of two different species of elephant trunk, a new continuum structure which matched the key features of elephant trunk was designed. Based on analysis of the underlying elephant trunk's grasping mode, a novel kinematics model was proposed. Contrast to traditional robot kinematics which focused on end effector's position and posture, the proposed continuum manipulator kinematics focus on the center of manipulator's position and posture, which is more effective when trunk robot realizing grasp and establishes the foundation for its application. Finally, three typical grasping experiments were implemented. The experiment results showed that the manipulator could conduct wrap/pinch manipulations effectively for both small objects and bigger ones.

Keywords: fruit harvesting, continuum manipulator, kinematics, bionics, Jacobian, singularities

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1 Introduction

Tongues, trunks, and tentacles demonstrate an amazing variety of abilities by which animals dexterously interact with each other and manipulate their environment[1]. For instance, an elephant wraps its trunk around straw and picked it off the ground. Continuum manipulators were inspired by the biological world[2]. These manipulators were featured with a backbone-less structure similar to such biological counterparts as tongues, trunks, and tentacles. Like these organisms, a continuum manipulator could use the entire length of its arm to grasp objects of different shapes and sizes firmly. Potential applications of continuum robots included navigation through congested and unpredictable environments, and operating fragile objects such as fruits and vegetables.

The origin of continuum robotics was generally traced back to the creation of serpentine robots in the late 1960s[3]. For example, a continuum arm named ORM was created in 1965 by Stanford students Victor Scheinman and Larry Leifer[4]. The arm could extend by inflating several of 28 balloons sandwiched between seven metal disks. But, at that time continuum design had some weakness, such as limited lifting capability and accuracy, poorly understood kinematics and dynamics. In 1970s, hyper-redundant robots developed sustainably. Hirose and his team developed a series of snake-like

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robots[5] based on an "Active Cord Mechanism (ACM)" model.

From 1980s to 1990s, continuum robotachieved great development. The first industrial continuum manipulator was developed by Larson in 1982[6]. The elements of the continuum manipulator were interconnected via cables. Compared to conventional robot arms, the manipulator had very good rigidity in the bending plane of the element, high torsional resistance and lower manufacturing costs. While other academic achievements included shape memory alloy servo actuator for active endoscope[7], miniature pneumatic or hydraulic actuators applied as robot fingers[8], an in-pipe micro-robot[9], KSI tentacle manipulator for nuclear decontamination[10], 12-DOF JPLs serpentine robot for inspection[11], Shape memory alloy active forceps for laparoscopic surgery[12] and amadeus dexterous subsea hand[13].

In 21st century, much foundational work to establishthe theoretical framework for analysis of continuum robots early in this decade has come from the research group of Walker et al.. Continuum robots such as 'Elephant trunk' manipulator, Air-Octor and OctArmwere designed and analyzed by the Walker group in succession[14-18]. Meanwhile, the OC robotics company developed the first commercial continuum robot arm (OC robotics' snake-arm)[19]. Festo developed a bionic handling assistant using bellows structure[20]. Some continuum robots actuated by pre-curved Nitinol concentric tubes or tendon were applied in medicine such as catheters,colonoscopies[21-27], etc. Continuum robots have also made a significant impact in medicine. Continuum devices were used for surgery including flexible needles (Webster et al. 2009)[28], laparoscopic tools (Peirs et al. 2003)[29], and laser manipulators (Harada et al. 2007)[30].

The differences between traditional rigid-link robots and continuum robots are not only in mechanical structure, but also in mathematic modeling. Link lengths and joint angle were used to define traditional rigid-link robots' pose. But these were non-explicit for continuum robots. Thus, continuum robots modeling became a great challenge. Two modeling approaches were proposed in the last 50 years: general model[31,32] and approximation model[33]. Currently, the piecewise constant-curvature approximation model[34] has been applied widely. The model had advantages in the aspect of trajectory planning, but it was too complicated for grabbing. Therefore, more improvements are still needed.

In this study, a fruit harvesting continuum manipulator and its kinematics model were proposed. The proposed kinematics model is suitable for exsiting continuum robots.

2 Continuum manipulator design

2.1 Trunk bionics

The trunk, the elephant's most prominent characteristic, consists of muscle with no bone. The trunk of an adult elephant actually has only six major muscle groups, which are subdivided into over 100 000 muscle units[35]. A trunk can perform three different movements: bending in all directions, elongation and twist. There are two main species of elephants in nature: the African elephant and the Asian elephant. The trunks' physiological structure difference between the two elephant species caused difference of grasping method, as shown in Figure 1. The African elephant has two finger-like lobes on the tip of its trunk, where the Asian elephant only has one. The African elephant is able to wrap objects with the two finger-like lobes, while the Asian elephant scoop up objects with its entire trunk. Both species use their trunks to strip vegetation from branches and to pull grasses from the ground.

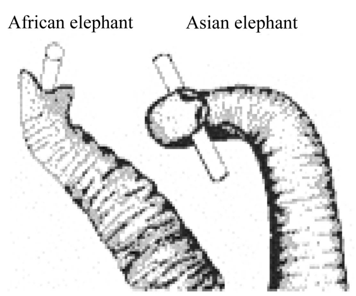

Figure 1 African vs. Asian elephant trunk grasping

2.2 Continuum manipulator mechanical design

In this paper, the characteristics of two species elephant trunk are combined to make contributions to a fruit harvesting continuum manipulator design based on flexible pneumatic actuators (FPAs) and flexible pneumatic bending joints (FPBJs). The FPBJ and FPA were introduced in previous work[36]. When the FPA was pressurized, it elongated in the axial direction. And, when the FPBJ was pressurized, it bent in one direction.

As shown in Figure 2, the manipulator was divided into two sections (section Ⅰ and section Ⅱ) to mimic the finger-like lobes and the trunk body respectively. The section Ⅰ was consisted of two flexible pneumatic bending joints (FPBJs), and compressed air was supplied to the FPBJs by a flexible tube aligned with the section central axis. Pressurization of the FPBJs produced clamping forces to pick up small objects. The section Ⅱ was assembled with twelve flexible pneumatic actuators (FPAs) which were sandwiched between five plates at 120° intervals. When the FPAs were pressurized respectively, the section Ⅱ could realize bending in any direction and/or elongation, with which larger objects could be scooped up. The shape of the section Ⅱ can be summarized as four different forms. And the four typical forms were shown in Figure 3. Therefore, the section Ⅱ can be regarded as a spatial curvewhen it moves.

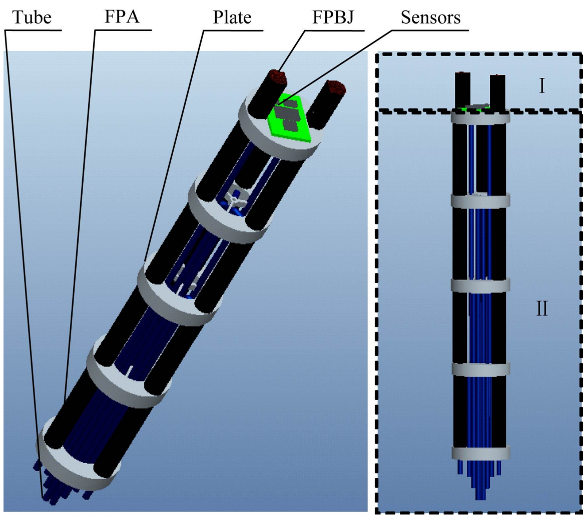

Figure 2 Prototype of the continuum manipulator

2.3 Continuum manipulator electrical control system design

Figure 4 provided an overview of the electrical setup. An ARM-based embedded system was used to control the manipulator. The model of embedded system's main control ship was stm32f407. Pressure in the FPAs was obtained by the embedded system and converted into analog by two digital to analog converters (DAC, DAC6578) to control the thirteen proportional valves. Several sensors were applied to measure the manipulator's posture and position. For instance, two flexible sensors (FLX-03) were assembled at the finger-like lobes to gauge their bending angle. 3-axis geomagnetic sensor, 3-axis accelerometer (ADXL325) and gyroscope (ADXRS622) were assembled on the manipulator to gauge its pose.

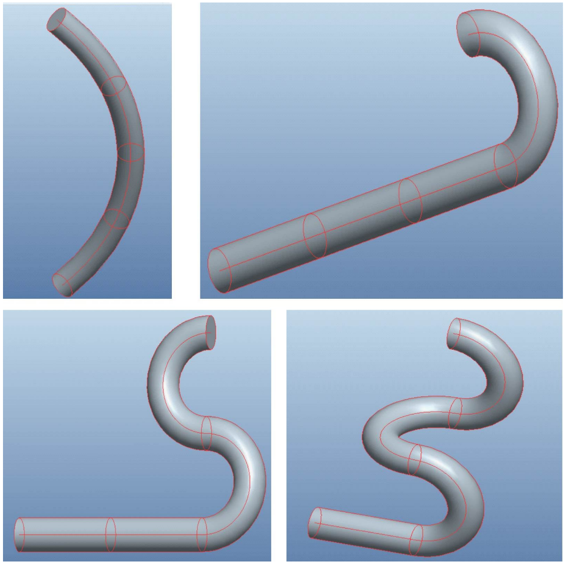

Figure 3 Four typical forms of section Ⅱ

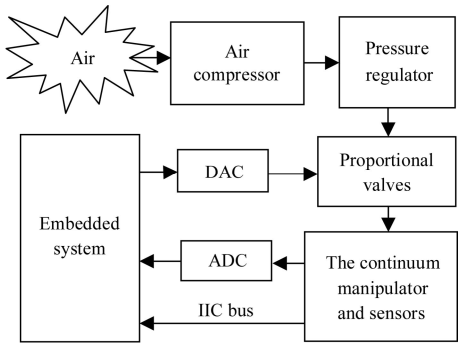

Figure 4 Electrical control system diagram of continuum manipulator

3 Kinematics model

To extract the full physical potential from the continuum manipulator, its kinematics model must be deduced. But almost all previous approaches either did not address trunk orientation or solved them only for limited kinematic models. These restricted the continuum robots' potential applicability[37]. A kinematics formulation for continuum robots was proposed which produced complete results for both task-space position and orientation in Jones (2001). In this paper, some of the ideas from Jones (2001) was modified and extended, a new kinematics formulation for continuum robots was proposed.

3.1 Posture and position description

As shown in Figure 5[38] and Figure 6, an elephant scooped up objects with its entire trunk. Contrast to traditional rigid robots, continuum manipulators paid more attention to enveloping objects not the end effector's pose. In other words, the manipulator's shape and position are the key parameters of the control system. The simplifying grasping model was to approximate the robot as an arc, so the center of arc was the key to fulfill the grasp. Hence, the new kinematics model proposed in this paper focused on the posture and position of the center.

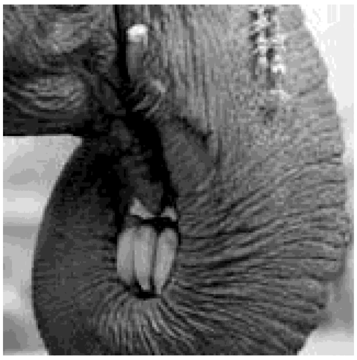

Figure 5 Elephant trunk's grasping photo

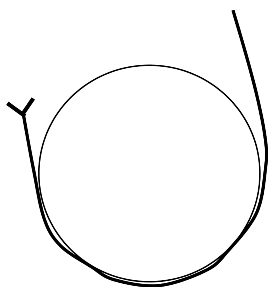

Figure 6 Elephant trunk's grasping mode

In traditional robot kinematics, homogeneous transformation matrix($A(\theta,d)$) to calculate the position and orientation was derived with Denavit-Hartenberg (D-H) method, which transferred robot structural parameters (θ,d) to task coordinate vector ($\boldsymbol{x}$). But, when the continuum manipulator was approximated as an arc, the translation joint (d) and the revolute joint (θ) were non-explicit. Instead, arc length (s), curvature (k) and bending direction angle (φ) were applied to describe the continuum manipulator. Thus a new vector q=[s k f] was defined as continuum manipulator's joint variable.

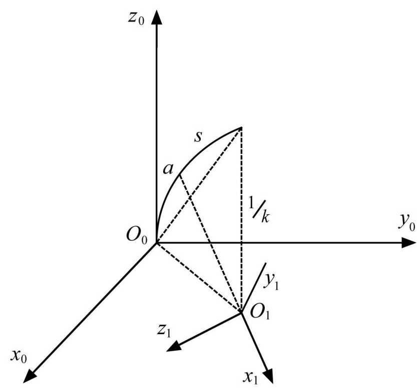

Figure 7 Geometric diagrams of continuum manipulator

As Figure 7 showed, the center O_1 was virtual, and did not attach on the manipulator. According to the basic D-H method for establishing the coordinate system of the last link, the coordinate system of O_1 was defined. Where axis z_1 was define as vector perpendicular to the manipulator bending plane. And axis x_1 was a vector connecting the midpoint of the arc (a) with the center (O_1), and its direction was from point a to point O_1. Thus, the resulting rotate matrix was as follows:

$$ {}_1^0\mathbf{R} = \begin{bmatrix} \cos\phi\cos\frac{ks}{2} & -\cos\phi\sin\frac{ks}{2} & -\sin\phi & 0 \\ \sin\phi\cos\frac{ks}{2} & -\sin\phi\sin\frac{ks}{2} & \cos\phi & 0 \\ -\sin\frac{ks}{2} & -\cos\frac{ks}{2} & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Further, according to Figure 5, the position of center O_1 ($\boldsymbol{x}(\boldsymbol{q})$) could be described as follows:

$$\begin{cases} x = \frac{1}{k}\cos\Phi \\ y = \frac{1}{k}\sin\Phi \\ z = 0 \end{cases} \quad (2)$$

Thus, the resulting homogenous transformation matrix was as follows:

$$ {}_1^0\mathbf{T} = \begin{bmatrix} \cos\phi\cos\frac{ks}{2} & -\cos\phi\sin\frac{ks}{2} & -\sin\phi & \frac{1}{k}\cos\phi \\ \sin\phi\cos\frac{ks}{2} & -\sin\phi\sin\frac{ks}{2} & \cos\phi & \frac{1}{k}\sin\phi \\ -\sin\frac{ks}{2} & -\cos\frac{ks}{2} & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

3.2 Jacobian matrix and singularities

According to the previous analysis, the Jacobian of a continuum manipulator could be divided into two terms, center linear velocity $\mathbf{J}_v$, and center angular velocity $\mathbf{J}_w$, so that the overall Jacobian was

$$\mathbf{J}=\begin{bmatrix}\mathbf{J}_v\\ \mathbf{J}_w\end{bmatrix} \tag{4}$$

where, $\mathbf{J}_v$ and $\mathbf{J}_w$ were derived form the partial derivatives of manipulator position (Equation (2)) and pose (Equation (1)) respectively. So that

$$\mathbf{J}_v=\frac{\partial \mathbf{x}(\mathbf{q})}{\partial \mathbf{q}_i}=\begin{bmatrix}0 & -\frac{1}{k^2}\cos\phi & 0\\ 0 & -\frac{1}{k^2}\sin\phi & 0\\ 0 & 0 & 0\end{bmatrix} \tag{5}$$

$$\mathbf{J}_w=\frac{\partial \mathbf{R}(\mathbf{q})}{\partial \mathbf{q}_i}=$$

$$\begin{bmatrix}
-\frac{k\cos\phi\sin\frac{ks}{2}}{2} & -\frac{s\cdot\cos\phi\sin\frac{ks}{2}}{2} & -\sin\phi\cos\frac{ks}{2}\\
-\frac{k\sin\phi\sin\frac{ks}{2}}{2} & -\frac{s\cdot\cos\phi\sin\frac{ks}{2}}{2} & \cos\phi\cos\frac{ks}{2}\\
-\frac{k\cos\frac{ks}{2}}{2} & -\frac{s\cdot\cos\frac{ks}{2}}{2} & 0\\
-\frac{k\cos\phi\cos\frac{ks}{2}}{2} & -\frac{s\cdot\cos\phi\cos\frac{ks}{2}}{2} & \sin\phi\sin\frac{ks}{2}\\
-\frac{k\sin\phi\cos\frac{ks}{2}}{2} & -\frac{s\cdot\sin\phi\cos\frac{ks}{2}}{2} & -\cos\phi\sin\frac{ks}{2}\\
\frac{k\sin\frac{ks}{2}}{2} & \frac{s\cdot\sin\frac{ks}{2}}{2} & 0\\
0 & 0 & 0\\
0 & 0 & 0\\
0 & 0 & 0
\end{bmatrix}$$

Typically, robots exhibit inherent singularities and boundary singularities due to their mechanical design. According to the Jacobian formulation, the continuum manipulator designed and analyzed in this paper did not process workspace boundaries singularities. And the only singular configuration occurred when the manipulator was straight (k=0). In practical applications pre-curving the manipulator at the beginning was an alternate method to eliminate this singularity.

4 Implementation

The prototype of continuum manipulator was manufactured. And its weight and length were 230 g and 400 mm, respectively. Because of the processing technology of FPAs, the maxim system air pressure was 0.6 MPa. The arc length (s) and curvature (k) of manipulator had their limitations too. Therefore, the size of objects scooped by the manipulator should be in a certain range. Lager objects could not be scooped because of the arc length limitation, and smaller objects could not be scooped because of the curvature limitation. But, smaller objects could be pinched by the manipulator instead.

To test its load capacity, limitation of operation size and compliance, a series of experiments were designed, including scooping and pinching difference objects.

When the manipulator scooping different objects, the arc length (s) and curvature (k) can be calculated according to the kinematics model derived in the paper. And the air pressure inside FPAs can be calculated according to the FPAs' characteristics and geometry. All calculations were fulfilled in the embedded system. And the results were outputted to proportional valves through the DACs.

The air pressure inside the chambers of the two FPBJs was controlled by one proportional regulator, which can theoretically ensure that they have the same working process and behavior. And their closed loop control can be achieved when the data from two flexible sensors (FLX-03) was read in real time.

Experiment picture shown in Figure 8 implied that various objects with different sizes can be handled by the developed continuum manipulator. For smaller objects (such as small tools, small oranges shown in the Figure 8), the continuum manipulator operated them with the finger-like lobes. The finger-like lobes could fulfill pinching and wrapping. For larger objects (such as an apple shown in the Figure 8), the continuum manipulator could scoop it up with its whole body. The manipulator not only can handle circular object, but also can handle square object, such as plastic box shown in Figure 8.

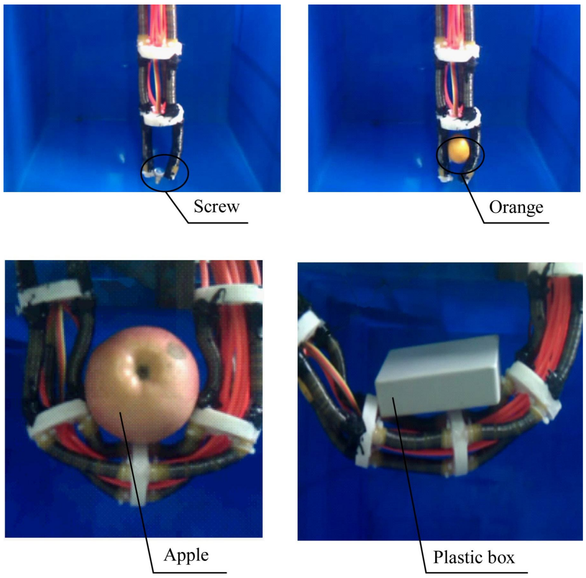

Figure 8 Experiment picture

According to the experimental data, the maximum weight of objects handled by continuum manipulator was 200 g, and the maximum diameter of objects was 100 mm.

5 Conclusions

A new type of continuum manipulator for fruit harvesting inspired by elephant trunk was proposed in this study. The continuum manipulator could elongate and bend in any direction. And based on piecewise constant-curvature approximation model, its kinematics model was proposed. The model which simplified the original continuum robot kinematics model can be applied to other continuum robots. It can provide a theoretical basis for the further development of continuum robot. A prototype of continuum manipulator was manufactured and tested. According to the experimental data, its load capacity met the requirements temporary, but need to be improved for further study. The continuum manipulator can be applied to fruit harvesting for its compliance and no damage.

Further study is necessary to reconcile following problem:

1) The structure of continuum manipulator should be optimized further to improve its load capability.

2) The manipulator's dynamic model should be studied.

3) More effective algorithm should be used in grasping.

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[References]

[1] McMahan W, Jones B, Walker I, Chitrakaran V, Seshadri A, Dawson D. Robotic manipulators inspired by cephalopod limbs. Proceedings of the Canadian Engineering Education Association, 2011.

[2] Neppalli S, Jones B A. Design, construction, and analysis of a continuum robot. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2007: 1503–1507.

[3] Webster R J, Jones B A. Design and kinematic modeling of constant curvature continuum robots: A review. The International Journal of Robotics Research, 2010; 29(13): 1661–1683.

[4] Calamia J. Artifacts from the first 2000 years of computing. Spectrum, IEEE, 2011; 48(5): 34–40.

[5] Hirose S, Yamada H. Snake-like robots. Robotics & Automation Magazine, IEEE, 2009, 16(1): 88–98.

[6] Larson O, Davidson C. Flexible arm, particularly a robot arm: U.S. Patent 4,393,728. 1983-7-19.

[7] Ikuta K, Tsukamoto M, Hirose S. Shape memory alloy servo actuator system with electric resistance feedback and application for active endoscope. Proceedings of IEEE International Conference on Robotics and Automation, 1988: 427–430.

[8] Suzumori K, Iikura S, Tanaka H. Applying a flexible microactuator to robotic mechanisms. Control Systems, IEEE, 1992; 12(1): 21–27.

[9] Takahashi M, Hayashi I, Iwatsuki N, Kohichi Suzumori K, Ohli N. The development of an in-pipe microrobot applying the motion of an earthworm. Proceedings of 5th International Symposium on Micro Machine and Human Science, 1994: 35.

[10] Immega G, Antonelli K. The KSI tentacle manipulator. Proceedings of IEEE International Conference on Robotics and Automation, 1995, 3: 3149–3154.

[11] Paljug E, Ohm T, Hayati S. The JPL serpentine robot: a 12-DOF system for inspection. Proceedings of IEEE International Conference on Robotics and Automation, 1995, 3: 3143–3148.

[12] Nakamura Y, Matsui A, Saito T, et al. Shape-memory-alloy active forceps for laparoscopic surgery. Proceedings of IEEE International Conference on Robotics and Automation, 1995, 3: 2320–2327.

[13] Lane D M, Davies J B C, Robinson G, O'Brien D J, Sneddon J, Seaton E. The AMADEUS dextrous subsea hand: design, modeling, and sensor processing. IEEE Journal of Oceanic Engineering, 1999; 24(1): 96–111.

[14] Hannan M W, Walker I D. Theelephant trunk manipulator, design and implementation. Proceedings of IEEE/ASME International Conference on Advanced Intelligent Mechatronics, 2001, 1: 14–19.

[15] Gravagne I A, Walker I D. Manipulability, force, and compliance analysis for planar continuum manipulators. IEEE Transactions on Robotics and Automation, 2002; 18(3): 263–273.

[16] McMahan W, Jones B A, Walker I D. Design and implementation of a multi-section continuum robot: Air-Octor. Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, 2005: 2578–2585.

[17] Jones B A, Walker I D. Practical kinematics for real-time implementation of continuum robots. IEEE Transactions on Robotics, 2006; 22(6): 1087–1099.

[18] Neppalli S, Jones B A. Design, construction, and analysis of a continuum robot. Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, 2007: 1503–1507.

[19] Ocrobotics, INC. Robots for Confined Spaces.http://www.ocrobotics.com/applications--solutions/Accessed on [2010-7-09]

[20] Festo, INC. Bionic handling assistant – flexible and compliant movement. http://www.festo.com/cms/en_corp/9655_10218.htm#id_10218. Accessed on [2010-6-09].

[21] Sears P, Dupont P. A steerable needle technology using curved concentric tubes. Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, 2006: 2850–2856.

[22] Harada K, Zhang B, Shin E, Toshio C, Masakatsu G F. Bending laser manipulator for intrauterine surgery and viscoelastic model of fetal rat tissue. Proceedings of IEEE International Conference on Robotics and Automation, 2007: 611–616.

[23] Choi D G, Yi B J, Kim W K. Design of a spring backbone micro endoscope. Proceedings of IEEE International Conference on Intelligent Robots and Systems, 2007: 1815–1821.

[24] Camarillo D B, Milne C F, Carlson C R, Zinn M R, Salisbury J K. Mechanics modeling of tendon-driven continuum manipulators. IEEE Transactions on Robotics, 2008; 24(6): 1262–1273.

[25] Hu H Y, Li W D, Li J, Sun L N. Structure design and trafficability of colonoscopic robot. Journal of Harbin Engineering University, 2013; 34(2): 233–235.

[26] Gao P. Research on key technologies and experiments of a conoic microrobot. Shanghai Jiaotong University, 2012.

[27] Li Q, He B, Xie H. Dynamic Modeling and Simulation on Continuum Robot. Machine Design and Research, 2012; 28(2): 18–22.

[28] Webster R J, Romano J M, Cowan N J. Mechanics of precurved-tube continuum robots. IEEE Transactions on Robotics, 2009; 25(1): 67–78.

[29] Peirs J, Reynaerts D, Brussel H V, De Gersem G, Tang H W. Design of an advanced tool guiding system for robotic surgery. IEEE International Conference on Robotics and Automation, 2003: 2651–2656.

[30] Harada K, Zhang B, Shin E, Toshio C, Masakatsu G F. Bending laser manipulator for intrauterine surgery and viscoelastic model of fetal rat tissue. IEEE International Conference on Robotics and Automation, 2007: 611–616.

[31] Ivanescu M, Florescu M C, Popescu N, Popescu D. Coil function control problem for a hyperredundant robot. Proceedings of IEEE/ASME International Conference on Advanced Intelligent Mechatronics, 2007: 1–6.

[32] Rucker D C, Jones B A, Webster R J. A geometrically exact model for externally loaded concentric-tube continuum robots. IEEE Transactions on Robotics, 2010; 26(5): 769–780.

[33] Andersson S B. Discretization of a continuous curve. IEEE Transactions on Robotics, 2008; 24(2): 456–461.

[34] Xu K, Simaan N. An investigation of the intrinsic force sensing capabilities of continuum robots. IEEE Transactions on Robotics, 2008; 24(3): 576–587.

[35] Paul Mackenzie. The trunk. http://elephant.elehost.com/About_Elephants/Anatomy/The_Trunk/the_trunk.html. Accessed on [2009-5-10]

[36] Bao G J. Research on characteristics of flexible pneumatic actuator FPA and its application in multi-fingered dexterous hand design. Zhejiang University of Technology, 2006.

[37] Jones B A. Kinematic and implementation of continuum manipulators. Clemson University, 2005.

[38] Elefantasia, INC. The world of the Asian elephant.http://www.elefantasia.org/spip.php?article65&lang=en. Accessed on [2010-7-09]