Proceedings of the World Congress on Engineering and Computer Science 2011 Vol II
WCECS 2011, October 19-21, 2011, San Francisco, USA

Geometry Modeling and Simulation of the Wire-Driven Bending Section of a Flexible Ureteroscope

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***Abstract*—Research and development of biomedical engineering boost in recent years. In which the increasing employment of endoscopy proves itself a trustworthy surgical technology to replace the traditional operations. It is mainly because it lowers the surgical risk as well as the patient's healing time by performing non- or minimally invasive surgery. A flexible endoscope is able to adopt the tortuous channels within a human body. It enables surgeon to not only observe but also carry out therapy within the patient's body. It can thank to the tiny bending section embedded in the front of it. Although many products have been bringing to the market for decades, there is no systematic study about the design or specification of the endoscopes. The purpose of this research is to configure the information on designing the bending section of a flexible ureteroscope which is particularly used in urological surgery. Geometry modeling of the bending section consisting of one and two sub-sections will be given. A program is composed for simulating the deflection of the bending section with different values of the parameters.**

***Index Terms*—bending section, ureteroscope, wire-driven mechanism, continuum robot, constant curvature**

I. Introduction

URETEROSCOPE is one type of endoscopes which is specially design for the use in the urinary system. By different configurations, it can be classified as rigid, semi-rigid and flexible [1]. In this study, the focus is put on the flexible ureteroscope. Fig. 1 shows the popular models used nowadays. The major characteristic of a flexible ureteroscope is the embedment of the deflection mechanism. This deflection mechanism mainly consists of the control body and the bending section as shown in Fig. 2.


(a) Gyrus ACMI DUR-8 Elite (b) Olympus URF-P5

Fig. 1. Popular models using in the current ureteroscopy.

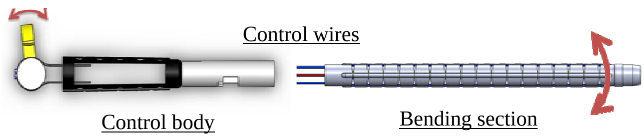

Fig. 2. Deflection Mechanism of a flexible ureteroscope

The deflection mechanism is a snake-like mechanism which distinguishes itself from the popular snake robots from the driven method. Basically, the snake robots have motors assembled at all the joints of the bending section and by controlling all the motors, the snake robots are able to move like a snake. However, for the deflection mechanism of a flexible ureteroscope, the bending section can deflect by controlling the wires passing through it. Thus this kind of actuation is called wire-driven. The control plant can also be removed from the moving part. Indeed, there are many industrial robot arms or manipulators adopting the similar mechanisms. They can be classified as discrete, serpentine and continuum. Among which, the continuum robots attract the most researchers to study. Work done by Robinson, el. [2] and Webster, el. [3] on continuum robots are complete and thorough. But the bending section is more similar to the serpentine robot arm. It has higher rigidity than continuum robots and is more flexible than discrete robots. For the simplicity, people would rather treat it as a continuum robot arm [4]. In this study, the comparison between these two types is given. Other than the wire-driven method, there are some existing actuation methods such as using Shape Memory Alloy [5], Electro Active Polymer [6][7], and Piezoelectric Ceramic [8] introduced by other researchers and scholars.

This paper continues our previous study [9]. The geometry modeling of the bending section will firstly be introduced. In which the relationship between the dimensions of the parts and the radius of deflection will be gone through. It follows by the validation of constant curvature assumption. Based on the geometry modeling and constant curvature assumption, simulations of the deflection for different configurations of bending sections will be demonstrated. It considers a bending section composed of one or two sub-sections as well as using one or two pairs of control wires. The last section is conclusion that summarizes the work present in this paper and raises some possible future work.

Manuscript received July 16, 2011; revised August 05, 2011. This work was supported in part by the MedServ International under Grant TM105679 (sponsor and financial support acknowledgment goes here.
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II. Geometry Modeling of the Bending Section

A. Description of formulation

In this study, the deflection of the bending section is assumed to be a planar motion. In other words, the locations of the parts composing the bending section can be defined in a global x-y coordinate frame. The formulation is reasonable because the ureteroscope is able to perform a planar motion only. If the urologist wishes to change the orientation of the ureteroscope, he has to rotate the entire ureteroscope to the desired angle and it is totally irrelevant to the deflection mechanism within the ureteroscope.

B. Assumption

A bending section can be formed by several sub-sections. In the following geometry analysis, the parts forming a single sub-section are assumed to be identical. The curvature along one sub-section is assumed to remain constant simultaneously while the bending section is under deflection. For simplicity, the analysis of the deflection can be reduced to consider a small section forming by two parts as shown in Fig. 3. Such assumptions are effective since most existing models in the market use this design for the ease of manufacturing.

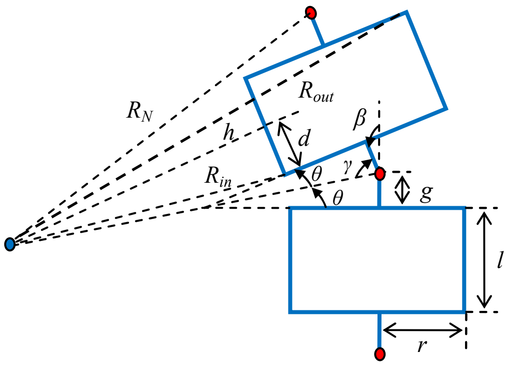

Fig. 3. Schematic diagram of the 2-part small section.

C. Notations

To study the bending, it is very important to clarify the key parameters in advance. The best way is to state some significant notations first: radius of the bending section (r), part length of the bending section (l), half the distance of the gap between 2 parts when they are in relaxed state (g), bending angle of a part (β), neutral radius of the bending (R_N), inner bending radius (R_{in}) and outer bending radius (R_{out}).

D. Derivation

Fig. 3 also demonstrates the counterclockwise deflection of the bending section at a certain moment. The geometry of the sub-section while deflecting can be concluded by equations (1) to (6).

$$\beta = 2\theta \quad (1)$$
$$\gamma = \pi/2 - \theta = (\pi - \beta)/2 \quad (2)$$

Then the neutral radius of the sub-section is

$$R_N = (d+g)/\cos\gamma = (d+g)/\sin(\beta/2) \quad (3)$$

Let $d = l/2$, then $h = (d+g)\cot(\beta/2) - r$ (4)

The inner bending radius of the whole bending section is

$$R_{in} = \sqrt{d^2+h^2} = \sqrt{d^2 + \left[(d+g)\cot\left(\frac{\beta}{2}\right) - r\right]^2} \quad (5)$$

The outer bending radius of the whole bending section is

$$R_{out} = \sqrt{d^2+(h+2r)^2} = \sqrt{d^2 + \left[(d+g)\cot\left(\frac{\beta}{2}\right) + r\right]^2} \quad (6)$$

In most of the cases, people are more interested in the minimum radii as well as the range of deflection of the bending section. Hence, R_{in} is the most concerned item by the doctors and the manufacturers of the endoscopes. Fig. 4 illustrates this case and the minimum value of R_{in} can be found by:

$$\frac{dR_{in}}{d\beta} = 0 \quad => \quad \beta^* = \beta_{max} = 2\tan^{-1}\frac{g}{r} \quad (7)$$
$$\therefore R_{in_{min}} = \left(\frac{l}{2}\right)/\sin\left(\frac{\beta}{2}\right) \quad (8)$$

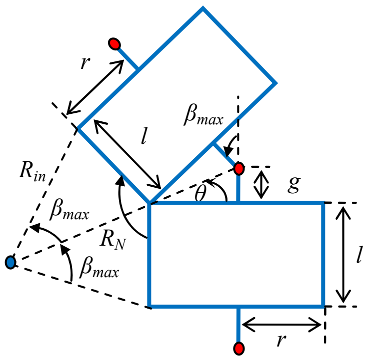

Fig. 4. Full deflection of the sub-section

Equation (7) also tells that the range of deflection of a part is constrained by the ratio of the gap distance and the radius of the bending section. At this moment, β reaches its maximum value and it can be denoted as β_{max}. Fig. 5 illustrates the dimension of $R_{in_{min}}$ of a bending section composes of identical parts.

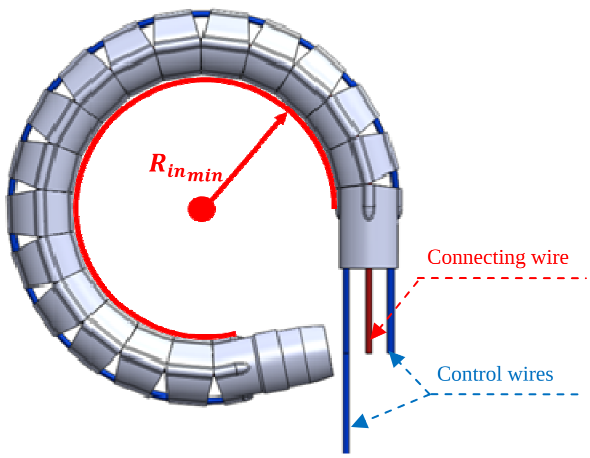

Fig. 5. Full deflection of bending section composed by identical parts

III. Constant Curvature Assumption

Afterwards, it is important to validate the assumption that the curvature along each sub-section of the bending section remains constant simultaneously while the bending section is under deflection. It helps to relate the angle of deflection of

ISBN: 978-988-19251-7-6
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

the parts within one sub-section. Not mentioning devices as specific as ureteroscope, there are a few studies about the continuum robots which are similar to the configuration of the bending section in this research. Most of them intend to treat the configuration of the bending section as a circular curve, thus the study would become much easier because of the simplification. It may be acceptable to treat it as an arc if precision requirement is not that serious. However, for the bending section of a ureteroscope, it is necessary to adopt the most realistic geometric features and dimensional values in order to obtain the most accurate outcome of calculations.

The curvature is the inverse of the neutral radius, i.e.

$$\kappa = 1/R_N = sin(\beta/2)/(d+g) \quad (9)$$

According this assumption, for any two sets of adjunct parts within a sub-section, they should have the same curvature. Suppose a, b denote any two sets of adjunct two parts within a sub-section of a bending section, then

$$\kappa_a = \kappa_b \quad => \quad \beta_a = \beta_b$$

Besides, for the sub-section consists of *n* parts,

$$-\beta_{max} \le \beta_i \le \beta_{max} \qquad where\ i = 1 \dots n$$

Thus it is easy to obtain the total angle of deflection of one sub-section,

$$\beta_{total} = n\beta_{max} \quad (10)$$

If the bending section consists of *N* sub-sections, the total angle of deflection of the entire bending section is

$$\beta_{total} = \sum_{i=1}^{N} n_i \, \beta_{i_{max}} \quad (11)$$

where n_i denotes the number of parts in the *i-th* sub-section. As a result, given the dimensions of the bending section, *N* and n_i can be determined by the required maximum angle of deflection. Other than the number of sub-sections, the number of pairs of control wires determines the deflection ability of the bending section. Each pair of control wires indeed represents one degree of freedom (DOF). In the following simulation, cases associate with both one pair and two pairs of control wires will be gone through.

However, if the bending section forming by identical parts is considered as a continuum robot arm, it can be treated as a circular curve as a whole. Since the neutral axis of the bending section does not extend or shorten no matter how it deflects, the length of it remains constant. In other words, the circular curve should be a constant and can be expressed by:

$$L_{arc} = R_{arc}\beta_{total} \quad \text{where} \quad L_{arc} = mL = m(2g+2d)$$
$$=> \quad R_{arc} = \frac{2m(d+g)}{\beta_{total}} = \frac{2m(d+g)}{m\beta} = \frac{2(d+g)}{\beta} \quad (12)$$

In order to compare R_N in equation (3) and R_{arc}, Fig. 6 shows both radii with respect to β_{total}. Here the bending section comprises 6 identical parts and the dimensions are:

$$d = 1.163mm, \qquad g = 0.139mm, \qquad r = 1.067mm$$

Then the range of total deflection angle is:

$$-89.21° \le \beta_{total} \le 89.21°$$

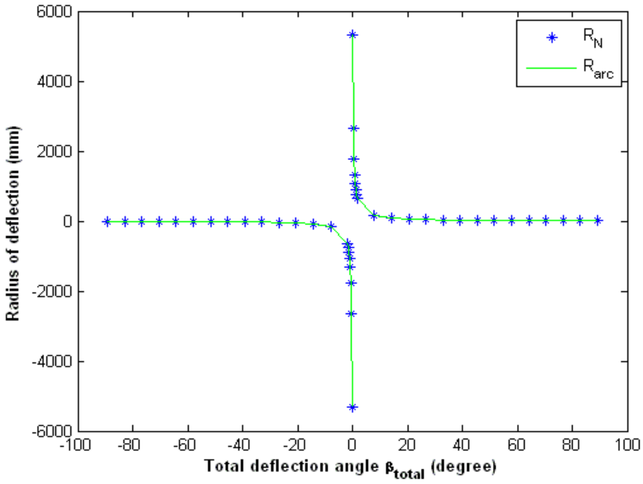

Fig. 6. Comparison of R_N and R_{arc} with respect to β_{total}.

From Fig. 6, both radii are very large when the deflection angle is very small. It is because the bending section is nearly straight which means the curvature of it is almost zero. In other words, the radius of deflection approaches to infinity. Meanwhile, it is very difficult to observe the difference between R_N and R_{arc}, therefore a parameter ε is introduced to be the ratio between these two radii. It can be simplified in the following expression:

$$\varepsilon = \frac{R_N}{R_{arc}} = \frac{(d+g)csc(\beta/2)}{2(d+g)/\beta} = \frac{(\beta/2)}{sin(\beta/2)} \quad (13)$$

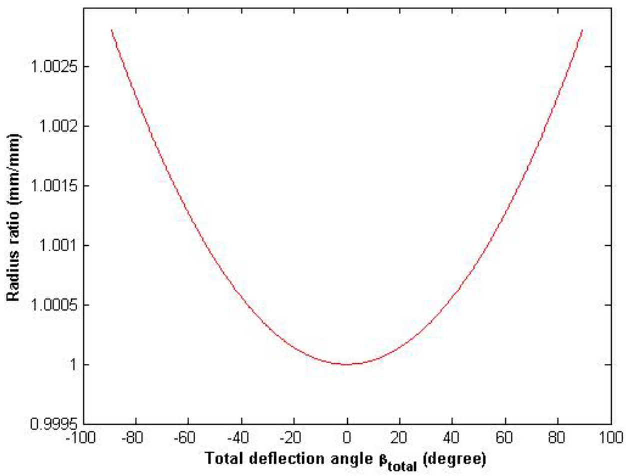

Fig. 7. Variation of ratio ε with respect to different β_{total}.

The curve in Fig. 7 represents the variation of the ratio when different total deflection angles of the bending section occur. It can be easily observed that when the total deflection angle is very small, the radius about the neutral axis is most likely equal to the radius of the circular curve. It can be analyzed mathematically from equation (13).

For very small $\beta/2$, $sin(\beta/2) \approx \beta/2 \quad => \quad \varepsilon \approx 1$

In other words, the deflected bending section can be regarded as a continuum robot arm when the bending angle of one linkage is sufficiently small. For a desired result of deflection, increasing the number of linkages can also

ISBN: 978-988-19251-7-6
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

enhance the similarity of the two patterns provided that the part length is short enough.

IV. Simulation of the Motion of the Deflection Mechanism

With the information from the previous section, a program is made for simulating the deflection of a bending section with adjustable dimensions. According to the given values of the parameters, simulations are possibly generated to provide a better observation or an easier way to study the motion of the deflection of the bending section. Because the urologist controls the ureteroscope to deflect very slowly, it can be assumed to be a static system. Also for simplicity, the deflecting angles between the parts are the same at any instant at this stage of study under the constant curvature assumption.

A. Construction of the simulation

The simulation mainly consists of two stages. The first one is initialization. In which some constant parameters will be defined and be calculated by the given dimensions of the bending section. Except the parameters mentioned in section II, the number of the pairs of control wires as well as their locations mounted on the bending section are necessary to provide too. The second stage is rendering the configuration of the bending section with respect to the part deflection angle. To configure the bending section, it is important to know where each part is located at that instant. By calculating the deflecting angles between two adjacent parts at an instant, it is possible to figure out the location of all the parts. Then it follows to orient the parts at their own positions. Since planar motion is considered at this moment, the parts are represented in the simulation by the contour of its cross section. As β_{max} is calculated in the initialization stage, the bending section in the simulation is able to stop at the maximum deflection.

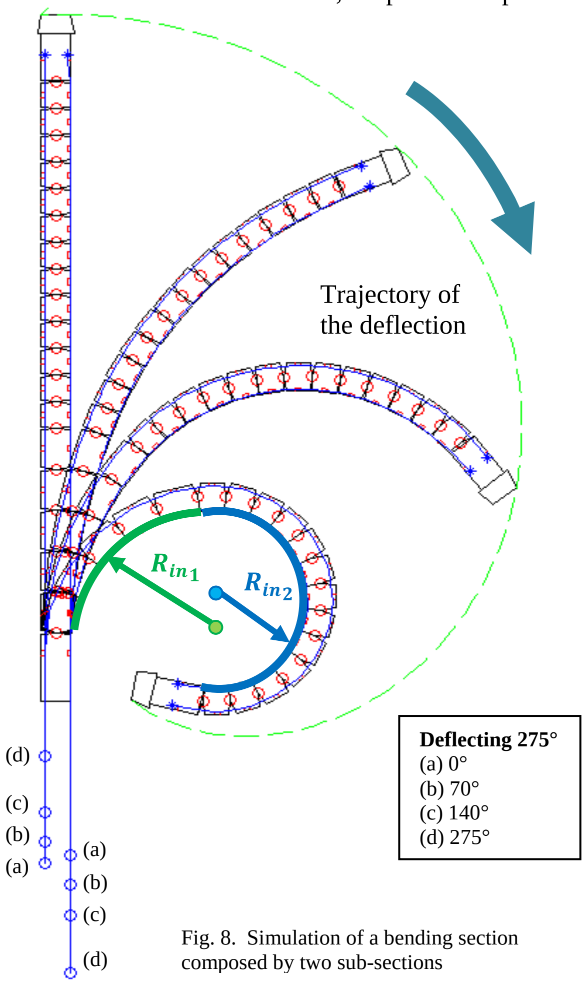

Fig. 8. Simulation of a bending section composed by two sub-sections

B. Controlled by a single pair of wires

As shown in the previous study [9], the wires mounted at different locations within a bending section would result in different extent of deflection. The parts without the wires string up would not involve in the deflection while a wire is being pulled except for the case that the wires are mounted at the distal end of a bending section. Here the case shown in Fig. 8 simulates a bending section composing of two sub-sections and is generated by the simulation program. It demonstrates the process of full deflection controlled by a pair of wires. Distinguished from the one shown in Fig. 3, this design contains two curvatures with respect to the two sub-sections. It is because the curvature relates to not only the gap distance and radius of a part, but also the length of it. It can be told from equation (8). Here the part length of the 1st sub-section and the 2nd sub-section are 3.048mm and 1.881mm respectively. Thus the corresponding inner radii are 11.6852mm and 7.2112mm.

C. Controlled by two pairs of wires

In Fig. 9, two pairs of wires are used to control the bending section. Such configuration enables the bending section to perform two stages of active deflections. Referring to Fig.9(a), the 1st pair of wires is mounted at the 12th part of the bending section, thus it can control the first twelve parts to deflect to 180° clockwise. Meanwhile, the 2nd pair of wires is mounted at the 18th part of the bending section. It enables one to pull the right wire to make the rest of the bending section deflect to the extra 90°. On the contrary, in Fig. 9(b), the left wire of the 1st pair is initially pulled to control the first six parts deflecting to 90° counterclockwise and then the left wire of the 2nd pair controls the rest to deflect to the extra 180° counterclockwise as well.

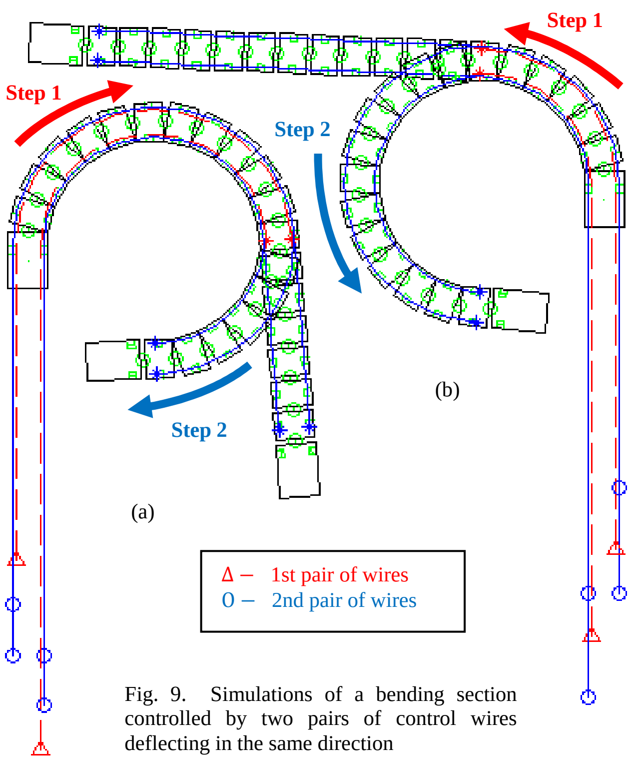

Fig. 9. Simulations of a bending section controlled by two pairs of control wires deflecting in the same direction

ISBN: 978-988-19251-7-6
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

Thanks to this simulation, another case of motion performed by this mechanism can be observed too. By adopting the configuration as shown on Fig. 9(b), the lower sub-section of the bending section can firstly deflect to 90° clockwise by pulling the right wire of the 1st pair. The left wire of the 2nd pair is then pulled until the rest of the bending section deflects to 180° counterclockwise. Fig. 10 demonstrates the case that the bending section reaches its maximum deflection.

With this simulation program, it is possible to change the parameters or dimensions of the bending section so that the corresponding performance can be observed. It is also compatible for an input function of bending angle β (t) solved from the dynamic equations in future study.

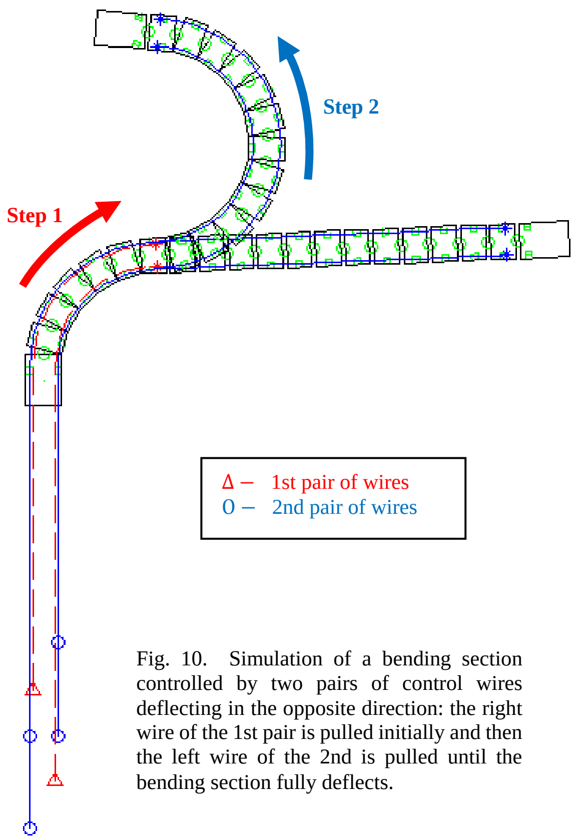

Fig. 10. Simulation of a bending section controlled by two pairs of control wires deflecting in the opposite direction: the right wire of the 1st pair is pulled initially and then the left wire of the 2nd is pulled until the bending section fully deflects.

V. Conclusion

As the bending section is very small in terms of the length and the radius of each part, it is necessary to consider the manufacturability during the design. In addition, according to some surveys, durability of the ureteroscope seems to be hard to improve [1]. It is because the material and the size of the bending section are constrained and sometimes the surgical devices damage the bending section inevitably. So far it is better to focus on improving the maintenance which can be achieved by lowering the cost and time. Hence, the ability of assembly should be considered. The purpose of this research is to state the critical issues for designing the bending section of a flexible ureteroscope. Meanwhile a simulation program is made to facilitate the designers to observe the feasibility as well as the motion of their proposed designs. Furthermore, a feasible and good design may lead to saving the time and money in the manufacturing process.

VI. Future Work

In the future, the work about the deflection mechanism of endoscopic devices should be focused on the force analysis. A successful force analysis can be a solid foundation for the development of automatic endoscopic surgery. The approach can be using the Lagragian method and the principle of least action by considering the minimum potential energy under some constraints such as the control wires must be fixed on certain parts. Herein all the bending angles are treated as generalized coordinates. It is expected that solving a set of Lagrange's equations will give the solutions of deflection angles and the input force which can be the applied moment to the wheel mechanism. By plugging in the angles in the simulation, the motion of the deflection mechanism can be observed. Hence, the derivation of the mathematical model can be verified. Of course, the prototypes of the designs will be made to carry out some experiments. It is always the best way to verify the theoretical work.

Other than application like ureteroscope, there are other possible applications for this wire-driven mechanism. Instead of a single system, two or more systems may be combined to form an integrated system. The integrated system maybe use in the biological inspired robots such as octopus robot. Besides, there is an innovative design of continuum robot which is called concentric tube continuum robot or also known as active cannulas is invented for the potential medical applications [3]. The special feature of it attributes to the bending actuation method. This operation is done by controlling the pre-curved elastic tubes at the "backbone" of the design to twist in order to transmit the rotation and translation to one another. More work should be carried out on the optimization of this design and it is expected a revolution of the deflection mechanism.

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ISBN: 978-988-19251-7-6
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)