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The Beam Theory-based Collision Force Detection of the Catheter Operating System

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***Abstract* - The catheter-based operating system is a specific surgical technique that can reduce the pain of the patients and permit a faster recovery compared with the conventional open surgery. It has gained increasing acceptance by the clinicians and patients. This technology has gradually matured. And it has started to extend from the therapeutic areas of cardiovascular disease to the cerebral vascular disease with the continuous development of the intravascular interventional operative technique. However, compared to the cardiovascular, the cerebral blood vessel is more fragile. So it is necessary to strictly control the operating force during the process of catheter insertion in order to avoid the irreparable damage. Simultaneously, the cerebral vascular is more narrow than the cardio blood vessel, which makes it impossible to use the catheter equipped with the special sensors during the surgery procedure. Hence it is hard to achieve the real-time monitoring and detection of the tool/tissue contact forces. Therefore, it is essential to realize the collision force detection in the distal of the catheter for the cerebral vascular interventional procedures. In order to improve the safety of surgery and avoid the contact force between the catheter and the blood vessel wall over the threshold value that the vessel can withstand. This paper proposed a method that modelling the distal part of the catheter using the beam theory that based on the morphology captured from the image. Meanwhile, a static force-tip model by using a pseudo-rigid-body 3R model have been developed and validated in this paper. The presented model detected the collision force at the catheter tip on the basis of the distal position and orientation information through extensive experimentally. It is demonstrated that the proposed method can estimate the constant force in the distal catheter without directly measuring the applied force at the tip**.

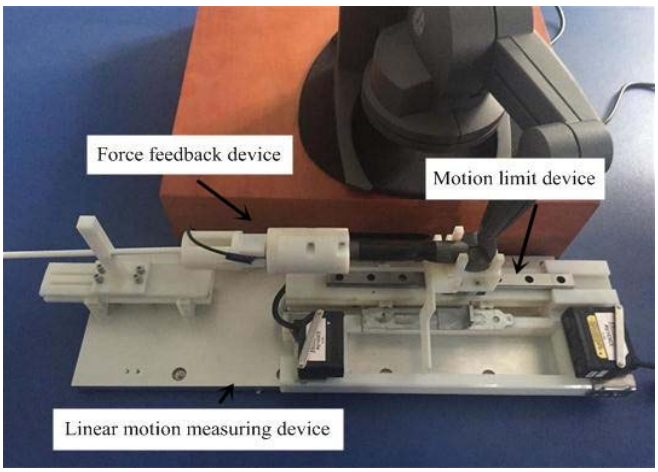
Index Terms – Cerebral vascular interventional surgery; Catheter operating system; Beam theory; Collision force; Pseudo-rigid-body model

I. INTRODUCTION

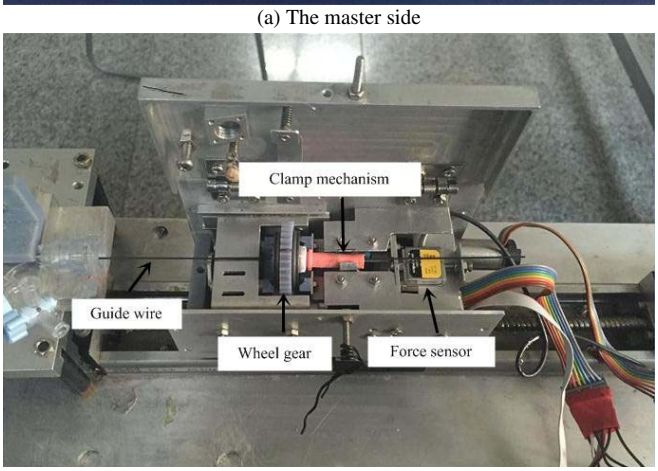
The cardiovascular and cerebrovascular diseases are the leading cause of death all over the world. As a new technology in the medical domain, the operation is a minimally invasive surgery. So it can provide the patients with smaller trauma, shorter recovery time and less pain compared to open surgery [1]-[2]. And for surgeons, less time consumption, higher precision, more securer and higher success rate are better than traditional operation.The minimally invasive vascular surgery is a major medical procedure that used to diagnose and treat cardiovascular disorder. It is an emerging medical procedure that under the guidance of medical imaging equipment, along the vessel operating the intervention catheter to reach the distant lesion, then implementing the minimally invasive treatment to the lesion position[3]-[4]. During the operation, a catheter is inserted into the blood vessels with the completion of the guide wire. Firstly, the surgeon makes a puncture on the femoral artery or the subclavian vein, following put the guide wire into the target vessels or target organ via the puncture point. Next, the surgeons push the guide wire carefully by the guidance of the digital subtraction angiography images and hand feeling until it arriving the specific section, and then pull out of the guide wire to complete the appropriate course of treatment. However, there are still various deficiencies exist. Currently, during the process of pushing the catheter, a more common practice is done by hand of the skilled operators directly to insert the catheter in the X-ray images or other gray image monitoring and guidance. As a new technology, it takes lots of the operating skills, for the surgical staff, making the catheter quickly and accurately reach the target position is a very difficult task. The errors or repetitive operations might cause some damage to the patients, when the catheter inserted into the vessel, bring a certain amount of risk to the surgery. In addition, the operation performed inside the body can not be directly monitored. At the same time, the contact force between the catheter and the blood vessel can not be detected. There is a long time for the doctors to have an operation in the x-ray radiation, this process would cause damage to the patient and physician.

The master-slave catheter operating system is proposed to provide more easier and accurate manipulation of the catheter insertion. It can reduce the harm caused by the X-ray the physician and medical staff. This system separate the doctors from the patients, after receiving the instruction from the slave side, doctors operate the main system side for the interventional procedures on the patients with the catheter, while from the various sensors installed on the slave side to get the specific information in the body especially intravascular. The Sensei robotic catheter system (Hansen Medical, Mountain View, CA) developed a master/slave control system with the application of the wire-driven technology for remote navigation and control of an ablation catheter and widely used in clinical practice [5]. The console screen displays the real-time contrast image and the ultrasound

image. By 3D visualization module, this product can display three-dimensional image of the heart and the catheter in real time as well as a rough estimation of the tip contact forces on the screen [6]. Jayender et al. [7] proposed a master-slave robotic system which guides an active catheter instrumented with Shape Memory Alloy (SMA) actuators through the vasculature. The NIOBER magnetic navigation system (Stereotaxis, St.Louis, MO) provides magnetic navigation of a soft catheter [8]-[10]. Guolab developed a novel robotic catheter system for vascular interventional surgery [11]-[16]. However, none of these systems provide haptic feedback or any sort of force/impedance control of the catheter tip.



(a) The master side



(b) The slave side

Fig.1 The master-slave interventional surgery robot system

The passive catheter technology has also been developed in the vascular interventional procedures. The Corindus COMPANY provided a CorPath 200 System is the first vascular interventional surgical robot technology system used in the clinical trials by a passive catheter. It is consist of a catheterization mechanism and a console. A three-DOF manipulator locates the catheterization device to a surgical site that suitable for the patients. Doctors handle the control lever and there is a touch screen outside the operating room. It provides the remote control to realize the indoor insertion of the catheter and the guide wire. Thereby, this system completes the completion of the entire vascular interventional procedures. But the system can not automatically switch the catheter and the guide wire, the doctor needs to assist completing this process during the interventional procedures in the operating room. However, whether have the auxiliary of the vessels three-dimensional reconstruction, the use of magnetic navigation technology, ultrasound images, or Master side force feedback collection, these improvements are mostly focused on security issues of the master-side, and the lack of the studies to the security policy for the slave-side.

The previous studies show that the forces applied by the catheter tip have a significant impact on the security of the interventional surgery. Excessive force could easily lead to severe cerebral vascular injury, while larger impact sensor volume and smaller cerebral vascular diameter, the size of the collision force can not be measured by using a sensor. We model the distal part of the catheter using the beam theory that based on the morphology captured from the image and detect the tool/tissue contact force by the pseudo-rigid-body model of the catheter tip, then investigate the performance of such a model. The developed model describes the in-plane bending of a catheter when the applied forces are also in the catheter plane. Notably, the proposed model does not require massive knowledge of the catheter internal structure and it can be applied with a fairly simple calibration step. An experimental setup is used to validate the proposed model empirically. In Section II, the experimental setup is described. The modelling method and the contact force estimation are presented in Section III. Section IV provides experimental results which are then discussed in Section V. Section VI concludes the paper with suggestions for future research.

II. System Design

Fig.1 shows a master-salve interventional surgical robot system structure designed in our previous works developed by Guolab that consists of two parts: the master side and the slave side [17]-[24].

The master side for the operation includes the force feedback device, the movement limited device, the measuring device of the linear displacement. It can simulate the operators' push and rotary motion that required in the surgery. At this point, the laser range finder will measure the push volume caused by the operator shoving the function lever, as well as the rotation angle can be detected by the phantom mechanical arm. Then it feedback the force to the operator though the master side (Fig. 1(a)). The slave side for the catheter insertion mainly consists of two linear motors, a rotary motor, a mechanical guide, a force sensor, a guide wire clamp which can detect the actual value of the displacement and the rotation, and feed back to the control system. Thus this side completes a closed-loop displacement control as shown in Fig. 1b. The red part is a guide wire clamp, the big gear is driven by a small gear on the bottom, and a DC motor controls the guide wire clamp to realize tighten and relax of the guide wire. There is a clamp mechanism which is used for fixing the guide wire clamp. It is controlled by a rotary motor to achieve tighten and relax of the guide wire. The yellow part is a force sensor, which is used to detect the force feedback signal from the slave. When the guide wire is contact with the vascular

wall in the moving process, go through the white connection part, the force feedback signal is transferred to the pressure sensor, so that we can get the force feedback information from the slave.

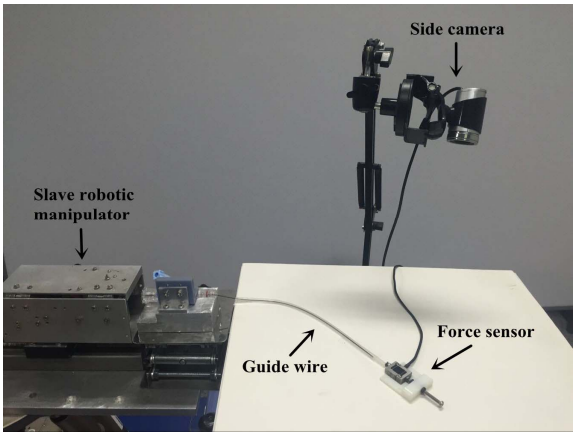


Fig.2 A view of the catheter tip, camera and the force sensor in the experimental setup

Figure 2 shows the experimental setup of the collision force detection. It has two main parts, one is the slave robotic manipulator system in the left side of the image that can control the guide wire forward and back. On the other side is the two-dimensional linear bench with the overall white background. The 0.76mm diameter angiographic guide wire is actuated by the slave robotic manipulator to get through the 3mm diameter medical soft tube with the length of 200mm to simulate the guide wire movement within the blood vessels in the human body. The catheter is the deflectable shaft that the distal part is out of the soft tube and its shape is monitored using a camera that acquires images with a resolution of 640 × 480, such that can provide the position and orientation information of the catheter tip. In order to measure the actual contact forces at the catheter tip, a micro force sensor (LA-S2, CN) is fixed to the experimental stage with a custom printed adapter.

III. Pseudo-Rigid-Body 3R Model of A Cantilever Beam

The goal of this paper is to develop a static model which describes the mapping between the distal catheter deformation and the force. A cantilever beam model may be used to describe the behavior of this segment of the catheter. The catheter is adjusted such that the applied forces and the bending of the tip all occur in a 2D plane. Several methods have been proposed to solve the problem of modeling a catheter. Numerical approaches have been used for modeling and simulating a catheter inside the vasculature. A number of these approaches describe the catheter as a multi-body system with rigid links and flexible joints [11]. Another category of numerical methods assumes that a wire-like object is composed of multiple beams and uses a finite element method (FEM) to model it [25]–[26]. Although FEM can be used to model the behavior of long flexible instruments, it is computationally expensive and may lead to inaccurate results if all the constraints are not known. Continuum robot theory is another approach to modeling a catheter [27]. The performance of continuum robots has been well studied and different models have been proposed [28]. In this model, a single section of the manipulator is considered as a cantilever beam which undergoes large deflection due to actuation by a single tendon. This approach requires detailed information of the actuators continuum robot which is not available for a catheter.

According to the study and analysis of the collision force detection method in the interventional surgical robot systems at this stage, we found that the current calculation precision is still not high and the calculative process is too complex to achieve the real-time contact force detection in the catheter tip during the interventional procedures and other issues. In order to solve the problem of these methods, this paper still uses the physical modelling method based on the catheter or guide wire to have an in-depth study of the collision force detection at the catheter tip.

Aim at the accuracy and the complexity requirement of the contact force detection in the new-type robotic interventional surgical system, in this paper, the cantilever model that the load applied at the free end is equivalent to the pseudo-rigid-body mode of the compliant mechanism. The Pseudo-rigid-body (PRB) models provide an easier and more efficient method of describing the force-deflection relationships of a compliant system that undergoes large deflections. The PRB of a cantilever beam has been studied extensively to the different loading conditions with high accuracy [29]-[30]. Su suggested a PRB 3R model of a cantilever beam to further improve the model accuracy for different load models [30]. The PRB 3R model replaces a flexible cantilever beam with four rigid links connected by three revolute joints and three torsional springs [30]. And it is an improvement on the PRB lR model [29] with higher accuracy.

In order to solve these issues and improve the accuracy of the model, a PRB 3R model for the catheter tip is presented to describe the force-deflection relationship of the catheter tip. The model parameters are determined such that the model will estimate the contact force applied at the catheter tip. The model performance is evaluated empirically and it is shown that the proposed model can define the relation of the contact force and different deflection condition of the catheter [31]-[33].

A PRB 3R serial chain for modelling a flexible beam subject to a combined end force and moment is showed in the Fig 3 that denote the deflection angles and spring stiffness by φ_1, φ_2, and φ_3 and k1, k2, and k3 respectively. The ratios of the four link length to the length of the beam are characteristic radius factors, denoted by γ_0, γ_1, γ_3, and γ_4 satisfying

$$\gamma_0 + \gamma_1 + \gamma_2 + \gamma_3 = 1 \tag{1}$$

Given external loads F_C, θ_F and M_Z on the tip of the 3R chain, the torques at the three pin joins are given by[34]

$$\begin{Bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{Bmatrix} = \left[J^T \right] \begin{Bmatrix} F_x L \\ F_y L \\ M_z \end{Bmatrix} \tag{2}$$

Where $F_x = F_C \cos\theta_F$ and $F_y = F_C \sin\theta_F$. And matrix $[J^T]$ is the transpose of the non-dimensional Jacobian of the 3R chain obtained by differentiating kinematic equation, written as [35]

$$[J^T] = \begin{bmatrix} -\gamma_1 s_1 - \gamma_2 s_{12} - \gamma_3 s_{123} & \gamma_1 c_1 + \gamma_2 c_{12} + \gamma_3 c_{123} & 1 \\ -\gamma_2 s_{12} - \gamma_3 s_{123} & \gamma_2 c_{12} + \gamma_3 c_{123} & 1 \\ -\gamma_3 s_{123} & \gamma_3 c_{123} & 1 \end{bmatrix} \quad (3)$$

$$\begin{aligned} c_1 = cos\varphi_1, c_{12} = cos(\varphi_1 + \varphi_2) \ , c_{123} = cos(\varphi_1 + \varphi_2 + \varphi_3) \\ s_1 = sin\varphi_2, s_{12} = sin(\varphi_1 + \varphi_2) \ , s_{123} = sin(\varphi_1 + \varphi_2 + \varphi_3) \end{aligned} \quad (4)$$

Assuming that the joint torque is proportional to the joint deflection angles and the spring torque is proportional to the PRB angles, the following equation yields tip loads [30]

$$\tau_i = k_i \varphi_i, \quad i = 1,2,3 \quad (5)$$

$$\begin{Bmatrix} F_c L \cos\theta_F \\ F_c L \sin\theta_F \\ M_z \end{Bmatrix} = \left[J^T \right] \begin{Bmatrix} k_1 \varphi_1 \\ k_2 \varphi_2 \\ k_3 \varphi_3 \end{Bmatrix} \quad (6)$$

where J denotes the Jacobian of the 3R manipulator illustrated in Fig. 3, and L is the length of the deflectable shaft.

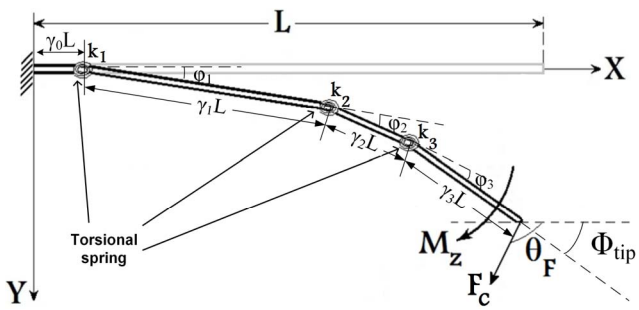


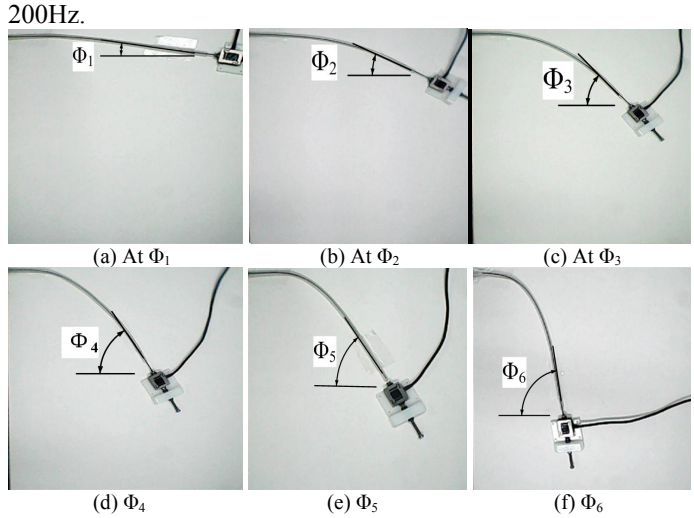
Fig.3 Pseudo-rigid-body 3R model

The optimal link parameters and spring stiffness values for the PRB 3R model are found by feeding the collected data into the optimization algorithm [31]

$$\begin{aligned} \gamma_0 = 0.05, \ \gamma_1 = 0.3, \ \gamma_2 = 0.4, \ \gamma_3 = 0.25 \\ k_{\varphi_1} = 1.09, \ k_{\varphi_2} = -1.18, \ k_{\varphi_3} = 1.12 \end{aligned} \quad (7)$$

where γ_i , i = 0,1,2,3 are the normalized link lengths and $k_{\varphi i}$, i= 1,2,3 are the normalized spring stiffness values.

In order to verify the suitability of the proposed collision detection methods based on 3R pseudo-force body model for the angiography guide wire , this paper design 6 different bending angle form of the deflecting guide wire is showed in the Fig.4, the guide wire is actuated by the slave robotic manipulator to get through the medical soft tube to simulate the guide wire movement within the blood vessels in the human body, the catheter is the deflectable shaft that the distal part is out of the soft tube and its shape is monitored using a camera in the vertical direction that acquires images such that can provide the position and orientation information of the catheter tip, meanwhile the measure the force sensor that fixed to the experimental stage measure the actual contact forces at the catheter tip. The image of each guide wire bending form captured by the camera can extract the guide wire trajectories by the binary processing, and use the guide wire terminal slope to calculate deflection angle, Φ_i, i = 1,2,3,4,5,6 at the end of the guide wire(Fig.5), the require date contact force F measured by the force sensor is collected at a sampling rate of 200Hz.



(a) At Φ_1 (b) At Φ_2 (c) At Φ_3

(d) Φ_4 (e) Φ_5 (f) Φ_6

Fig.4 Different bending form of the guide wire

If the position and orientation of the ablation tip are known, the contact force at the guide wire tip can be estimated using the optimization parameters value of the proposed pseudo-rigid-body (PRB) 3R model to solve distal collision force problem of the catheter-based interventional surgical robotic system. Finally, the contact force F that measured by the force sensor is compared with the value of F_c estimated by the presented model to evaluate the performance of the collision force detection method using the pseudo-rigid-body (PRB) 3R model.

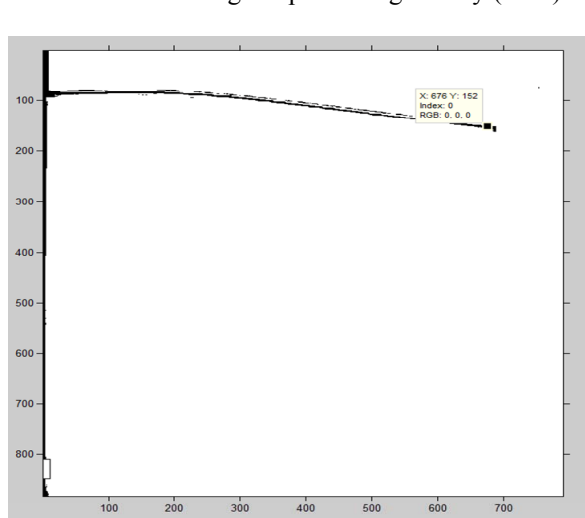
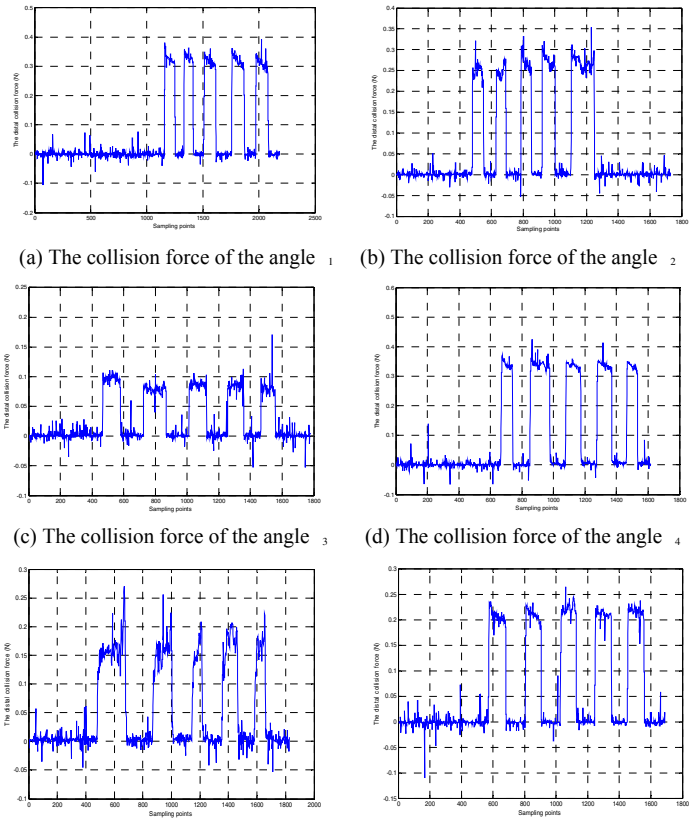


Fig.5 The guide wire movement locus obtained by binary processing

IV. Experimental Results

The performance of the pseudo-rigid-body 3R model for estimating the contact force at the catheter tip is evaluated experimentally.

In order to avoid measurement errors caused by the misuse of the operator, the guide wire is controlled to push and back for five times of the different bending angle with recording the collision force information generated at the catheter tip, and obtaining the average value as the contact force detected by the force sensor. The result is shown in the Fig.5.



(a) The collision force of the angle $_1$ (b) The collision force of the angle $_2$

(c) The collision force of the angle $_3$ (d) The collision force of the angle $_4$

(e) The collision force of the angle $_5$ (f) The collision force of the angle $_6$

Fig.5 The distal collision force results of the different tip angle

Comparing the actual contact force F measured by the force sensor with the contact force F_C estimated by the presented modelling method, the performance of the force estimation method based on the pseudo-rigid-body 3R model is assessed at different tip angle from each of the guide wire bending form and Table 1 summarizes the results.

The maximum experimental error is 2.62gf, the average error is 1.93gf, RMSE (root-mean-square error) is 1.89gf, have reached the requirement of the collision force detection. Due to the structure of their distal shaft, unidirectional catheters can apply such forces only if the contact force acts in the plane of the bent catheter. In practice, out-of-plane forces might act on the distal shaft. Nevertheless, the contact force should be the dominant force acting on the tip, otherwise the tip would slip away from the target tissue.

Thus, in this study, we have focused on the tip contact forces applied in the plane of the bent distal shaft.

TABLE 1: Performance of the force estimation at different guide wire form

Φ_i	F (N)	F_C(N)	Maximum Error{F_C} (gf)	Average Error{F_C} (gf)	RMSE{F_C} (gf)
Φ_1 = arctan0.3	0.076	0.103	2.62	1.93	1.89
Φ_2=arctan0.556	0.155	0.132			
Φ_3= arctan0.714	0.206	0.176			
Φ_4 = arctan1.414	0.261	0.227			
Φ_5 = arctan2	0.314	0.279			
Φ_6= arctan4.2	0.341	0.303			

V. Discussions

In the previous section, the performance of the pseudo-rigid-body 3R model in estimating the shape of the catheter tip was evaluated and statistical measures for model performance were provided in section IV. The factors that contribute to errors for all approaches include:

1) The error in measuring the tip angle and the horizontal and vertical components of the displacement due to camera registration error.
2) The inherent error of the pseudo-rigid-body 3R model and the error generated in the calculation process. This model equalizes the flexible guide wire into four rigid links that is connected by the torsion spring. The equivalent process have some internal errors in the calculation, at the same time the slope and angle measurement will produce some calculation errors;
3) Force Sensor has its own optimum operating temperature. As the experiment progresses, the sensor will continue to produce heat-induced temperature rise, thus affecting the measurement precision of the force sensor, resulting in the experimental error.

VI. Conclusions

An analytical 2-dimensional mapping between the actual collision force in the distal catheter and the evaluated force volume provided by the model of the catheter proposed in this paper. This model is the pseudo-rigid 3R model based on using a certain deformation beam model and it does not require extensive knowledge of the catheter internal structure. The suggested model was validated through experiments on the catheter and it was shown that the developed model is capable of estimating the shape of the distal section of the catheter if the amount of applied force is known.

A static analytical model for the catheter used in the interventional surgery which can be a first step towards designing a model-based force detection of the catheter tip is presented in the paper. This model can be used in the various kinds of the catheter bending to calculate the collision force along the catheter. Hence, we have focused on developing a general static model that can describe the catheter behavior. Extending the proposed model to a 3-dimensional model by considering out-of-plane bending, evaluating the model in more realistic experimental setups and providing real-time force-deflection calculations will lead to a generalized model

that could potentially be used to design a hybrid force/position or impedance controller for a robot-assisted catheter control system.

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