The master-slave catheterisation system for positioning the steerable catheter

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Abstract: This paper proposes a master-slave catheterisation system including a steerable catheter with positioning function and an insertion mechanism with force feedback. The steerable catheter is integrated with two magnetic tracking sensors for positioning. The distal shape of catheter is displayed with virtual vascular model to generate 3D guiding image to provide the relative relationship between the catheter and its surrounding vessels. The master-slave insertion mechanism with differential gear structure is designed with force feedback to assist surgeons to manipulate the catheter. It can implement pulling/pushing, rotating and bending/recovering the catheter. Based on this system, surgeons in the control room can utilise the master handle to operate the insertion mechanism for positioning the distal end of catheter with the assistance of 3D guiding image. The stability and accuracy of the system is validated in-vitro.

Keywords: master-slave; catheterisation system; steerable catheter; insertion mechanism.


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1 Introduction

Catheter ablation has become popular in the treatment for cardiac arrhythmias. The steerable catheters utilised are a kind of catheters which possess a flexible distal segment and equipped with several electrodes on the tip. These catheters are placed into the veins or arteries in the legs, and sometimes arm or neck and passed to the cardiac chambers (Ernst, 2008). After the location where the arrhythmia arises is determined, radiofrequency ablation or cryoablation is implemented using the catheter tip to ablate or destroy this abnormal pathway (Elhawary et al., 2008; Gomes, 2011). However, there are still limitations in the current ablation procedures.

Both the patients and surgeons suffer from the radiation under x-ray fluoroscopic guiding image which provides locations of the catheter and vasculature. Two commercial available remote-controlled catheter navigation system, Niobe® magnetic navigation system (Stereotaxis, USA) (Ramcharitar et al., 2008) and Sensei® robotic navigation system (Hansen Medical, USA) (Amin et al., 2005; Dogangil et al., 2010), have improved the operating environment of surgeons. They both provide remote manipulation of catheters which prevents surgeons from fluoroscopy exposure (Chun et al., 2008). There are also some research groups focusing on this. Janji and Janabi-Sharifi (2007) and Janji et al. (2008) described the kinematic model for the flexible steerable catheter, and implement the robot-assisted catheter manipulation. But in his research, there is no guiding image, which is necessary to facilitate the surgery. So surgeons can just use the third sensor to ensure the target point. Jayender et al. (2007) and Jayender and Patel (2009) has developed robot-assisted active catheter insertion, in order to implement a master-slave control strategy with respect to an active catheter actuated by shape memory alloy more accurately and safely. Piere et al. (2010) constructed a teleoperation system using 5-DOFs concentric tube robot for minimally invasive surgery, which was based on combing pre-curved elastic tubes, and a general kinematic model was presented to accomplish precise real-time control. Jun et al. (2011) developed a novel force-reflecting robotic catheter navigation system with a network-based master-slave way. A 3-degree of freedom robotic manipulator was designed to operate a conventional cardiac ablation catheter safely. Jian et al. (2010) and Nan et al. (2010) developed a catheter operation system with a precise master-slave remote control. It consisted of a master-slave device used to replace the manual operation, force sensors based on the pressure sensitive rubber, web camera equipped to realise visual feedback. The system could avoid danger effectively with the help of visual and haptic feedback. However, the patient is left in the operating table exposed to x-rays in the procedure of surgery. It is of great importance to reduce the fluoroscopic usage and improve the safety.

The authors proposed a catheter navigation scheme in their previous work, of which the core is the combination of positioning steerable catheter with a preoperative 3D navigation image (Liu et al., 2010). This catheter implements its steering performance by pulling and relaxing the wire running through its lumen with the knob in a handle. Since the difficulties of steerable catheter’s fabrication and assembly and its inherent property, there is no definite corresponding relationship between the movement of knob and the bending of the catheter. Generally, it is non-linear with hysteresis, and it is difficult for surgeons to obtain a desired bending angle smoothly. It requires repeated attempts and hence brings uncertainty to the bending range of the catheter. The efficiency, success rate and safety cannot be guaranteed. The prolonged intervention time makes the patient to suffer from more hurt and makes surgeons feel fatigue.

This paper develops a pull-wire catheter with two magnetic tracking sensors at its distal end, whose distal end integrated with reconstructed 3D virtual vascular model can be illustrated on the screen to facilitate the surgeons. Also the master-slave catheterisation system is constructed to manipulate the catheter, which can position the tip of catheter with high stability and accuracy.

The remainder of this paper is structured as follows. Section 2 introduces the steerable catheter and its design. Section 3 presents the insertion mechanism and its structure of force feedback. Section 4 indicates the master-slave catheterisation system and control strategy. Section 5 illustrates the experimental results and the effectiveness of master-slave catheterisation system. Section 6 concludes the paper.

2 The steerable catheter integrated with two magnetic tracking sensors

During the catheterisation, it is of great importance to know the pose of the distal end of catheter, especially the position relationship between the catheter and the surrounding vessels. Thus, z-ray image and angiography are used to provide the visualisation of both catheter and vascular anatomy. In this study, it is improved by utilising the magnetic tracking method. This kind of catheter must be provided with a pre-reconstructed 3D image (Fu et al., 2009).

2.1 Structure of the steerable catheter

The newly developed catheter is a 7Fr single-DOF steerable catheter integrated with magnetic sensors. Limited by the outer diameter of the catheter and the working environment, the diameter must be small enough to be embedded into the catheter tip; at the same time, the sensor should be as short as possible to make the catheter enter into thin and tortuous vessels easily. One suitable commercial available sensor is produced by Northern Digital Inc. (Canada), of which the dimension is 0.55 mm in diameter and 8 mm in length. It is 5-DOF sensor which can provide the position and orientation feedback, represented by \([p_x, p_y, p_z]\) and \([Q_0, Q_1, Q_2, Q_3]\) respectively. However, there is no information about its rotation and hence it is impossible to determine the bending shape of the distal end of catheter by
just assembling one such sensor into the catheter tip. In this study, two sensors are integrated into both sides of the bending segment. The structure and appearance of catheter are shown in Figure 1 and Figure 2. Besides two sensors, it also has two electrodes and a thermal couple to perform radiofrequency ablation and electrophysiology detection.

**Figure 1** The structure of steerable catheter (a) distal end of catheter (b) proximate handle of catheter

![Diagram of catheter structure](image)

**Figure 2** The appearance of steerable catheter (see online version for colours)

![Diagram of catheter appearance](image)

2.2 Visualisation of the distal end of catheter

Ideally, when the catheter bends within a 2D plane, the shape of catheter based on the circular arc supposition can be easily determined. However, in the actual bending process, since the catheter might be subjected to resistance force from the vascular wall and influenced by the accuracy of sensors, the bented catheter cannot be restricted within a 2D plane. In order to properly display the bending shape, the following procedures need to be done.

Considering the general situation, the orientation vectors of two sensors does not intersect, as shown in Figure 3. $S_1$ is the backward terminal of sensor 1 and $S_2$ is the forward terminal of sensor 2. Two lines determined by the position vector $p_i$ and direction vector $r_i$ of two sensors can be written as,

$$l_i = p_i + r_i \quad (i = 1, 2, t_i)$$

where $i = 1, 2, t_i$ denotes the distance from arbitrary point to $S_i$.

According to Figure 3, assume the distance of intersection points between two lines and the common perpendicular to be $t_1^0$ and $t_2^0$, and follow the conditions $M_1 M_2 \perp S_1 M_1$ and $M_2 M_2 \perp S_2 M_2$, the following equation set can be obtained,

$$
\begin{align*}
\begin{cases}
    r_1 \cdot (p_1 - p_2 + r_1 t_1^0 - r_2 t_2^0) = 0 \\
    r_2 \cdot (p_1 - p_2 + r_1 t_1^0 - r_2 t_2^0) = 0
\end{cases}
\end{align*}
$$

$t_1^0$ and $t_2^0$ can be calculated from (2), and the middle point of $M_1$, $M_2$, $M_0$, can be obtained. According to the assumption that the centreline of bending segment is circular arc, the bending plane locates in the plane fixed by three points, $S_1$, $S_2$ and $M_0$. The angle contained by $S_1 M_0$ and $S_2 M_0$, $\theta$, is taken as the centre angle. In Figure 3, $S_0$ is the middle point of $S_1$, $S_2$; $n$ denotes the normal unit vector of the plane containing bending shape; $s$ and $t$ represent the unit vectors of $S_1 S_2$ and $S_0 O$. They can be expressed by,

$$
\begin{align*}
s &= \frac{S_1 S_2}{S_1 S_2} \\
n &= \frac{S_2 M_0 \times S_1 M_0}{|S_2 M_0|} \\
t &= n \times s
\end{align*}
$$

**Figure 3** The bending shape of catheter integrated with two 5-DOF sensors

![Diagram of catheter bending shape](image)

According to geometric relationship, the radius of $S_1 S_2$, $R$, is $\frac{|S_1 S_2|}{2 \sin (\theta/2)}$. The coordinate of $O$ can be written as,

$$p_O = (p_1 + p_2) / 2 + R \cos (\theta/2) \cdot t$$

Through the following method, the mathematical expression of $S_1 S_2$ can be obtained. First, take $O$ as the origin, build a
local coordinate system \( \{ \mathbf{B} \} \), of which the \( \mathbf{x}_B \) coincides with \( \overrightarrow{OS}_B \) and \( \mathbf{z}_B \) with \( \mathbf{n} \). The homogeneous transformation matrix from \( \{ \mathbf{B} \} \) to \( \{ \mathbf{S} \} \) is given by,

\[
\mathbf{T}_{\mathbf{SB}} = \begin{bmatrix}
\mathbf{m} & \mathbf{n} \times \mathbf{m} & \mathbf{n} & \mathbf{p}_0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (5)

An arbitrary point \( P \) in \( \overrightarrow{S_1S_2} \) can be taken as the \( S_1 \) rotates around the axis \( \mathbf{z}_B \) for a certain angle, designated by \( \gamma \), \( \gamma \in [0, \theta] \). It can also be considered that \( \{ \mathbf{B} \} \) rotates for the same angle. Then the homogeneous transformation matrix from \( \{ \mathbf{B} \} \) to \( \{ \mathbf{S} \} \) is written as,

\[
\mathbf{T}_{\mathbf{SB}}' = \begin{bmatrix}
\cos \gamma & -\sin \gamma & 0 & 0 \\
\sin \gamma & \cos \gamma & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (6)

The coordinate of \( P \) is obtained to be \( \mathbf{T}_{\mathbf{SB}}'[R \ 0 \ 0]' \).

3 The insertion mechanism

For conventional minimally invasive surgery, the surgeon manually inserts the catheter through the blood vessels to reach the target point. When the distal end of catheter attaches to the vascular bifurcation or suffers from the resistance force blocking advancing, surgeons should pull back a bit or rotate the catheter, in order to adjust the position and orientation of catheter to advance it again. For the single curve steerable catheter used in clinical procedure, the bend of distal end of catheter is performed by surgeons at the proximate end. In this study, the insertion mechanism is located in the operating room to assist the surgeon to perform the catheterisation. The essential operations in the catheterisation include three kinds, pulling/pushing, rotating and bending/recovering.

Considering the medical environment, the design of insertion mechanism should meet the following requirements:

1. it should have high accuracy and stability, which can perform the minute displacement
2. it can operate in long time to make sure the safety in the procedure of catheterisation
3. simple operation and intuitive interaction are required to facilitate the surgery
4. the whole structure should be compact.

According to the current structure of catheter and the actual requests for the intervention, the operations of pulling/pushing and rotating should be performed near the puncture site: the entrance for catheters in the skin. Also, the catheter between its proximate end and the puncture site should be considered, so the mechanism should guarantee its pursuit motions to the whole catheter, in case it is pulled or twisted extremely.

3.1 The mechanical structure

The insertion mechanism has two components, the catheter manipulation part and the handle manipulation part, as shown in Figure 4.

**Figure 4** The schematic diagram of insertion mechanism (a) top schematic diagram of catheter manipulation part (b) front schematic diagram of catheter manipulation part (c) schematic diagram of handle manipulation part (see online version for colours)
The master-slave catheterisation system for positioning the steerable catheter

gear pair, then the catheter can be pulled or pushed; when they have the same velocities, there is no relative motion for the bevel gear pair, the active friction wheel has no rotation along its axis, only that along the axis of catheter, so the catheter can just be rotated.

Generally, the angular velocity of bevel gear and supporter for gear train is $w_r$ and $w_l$ respectively. The velocity to advance the catheter $v_d$ is calculated by,

$$w_f = (w_r - w_l)/(n_1 \cdot n_2)$$

$$v_d = w_f \cdot r_f$$

where, $n_1$ and $n_2$ denotes the gear ratio of bevel gear pair, and transmission gear pair, $w_f$ and $r_f$ denotes the angular velocity of active friction wheel and its radius. The angular velocity of rotation for the catheter is the same with $w_l$.

The latter can bend the distal end of catheter, as well follow the motions of the former, such as rotation and pull/push. When there is the reciprocation generated by the lead screw between the handle core and sliding sleeve, the wire attached in the sliding sleeve can be pulled or pushed to bend or recover the distal end of catheter. Based on the circular arc supposition, the distance $d_h$ between handle core and sliding sleeve decides the bending degree of catheter below,

$$\theta_c = l_h/R_c = l_0/(R_c - e)$$

$$d_h = l_h - l_0$$

where, $\theta_c$ denotes the degree of circular arc, $e$ denotes the offset distance between the wire and the central axis of catheter, $l_h$ and $l_0$ denotes the length of bending segment of catheter and wire.

3.2 Force feedback

To improve the force ambiance, force sensors are embedded into the active wheel to acquire the advancing force. In Figure 5, the active friction wheel contains inner wheel and outer wheel. The motion is transmitted to the outer wheel by the steel ball in the force sensors embedded in the inner wheel, while the outer wheel rotates to pull or push the catheter clamped by passive friction wheel.

In the intervention, collected force includes the contact force of catheter’s tip with surrounding vessels and the friction force between the catheter’s sheaths and vascular wall. It represents the whole effect. When the catheter is pushed, the force is collected by sensor A; when the catheter is pulled, the sensor B collects the force. Suppose there is no relative slide between the catheter and outer wheel, the static friction serving as the advancing force is given by,

$$f_a = f_t \cdot r_s/r_f$$

where, $f_a$ denotes the advancing/retreating force of catheter, $f_t$ denotes the force collected by the sensor A or B, $r_s$ denotes the embedded radius of the sensor.

Figure 5  The schematic diagram of force feedback structure (a) assembly drawing (b) exploded drawing (see online version for colours)

The force sensor is based on the pressure sensitive resistor, which has high-quality linear character. The circuit is designed to amplify the voltage signal, as shown in Figure 6. So according to the function of the integrated chip AD623, the amplified output voltage $V_o$ is calculated by,

$$V_o = (1 + 100 \kappa \Omega/R_G) \cdot (V_{o+} - V_{o-})$$

where, $R_G$ denotes the customised resistor, $V_{o+}$ and $V_{o-}$ are differential output voltage.

Figure 6  The force sensor and its circuit diagram (a) force sensor (b) circuit diagram (see online version for colours)

Before the sensors are assembled into the inner wheel, their calibrations should be made to obtain the relationship between load weight $L_a$ and output voltage $V_o$. The result is shown in Figure 7. The relationship is given by,

$$V_o = k_s \cdot L_a$$
where, \( k_s \) denotes the slope of linear fitting.

**Figure 7** The relationship between load weight and output voltage (see online version for colours)

![Graph showing the relationship between load weight and output voltage](image)

### 4 The master-slave system and control strategy

#### 4.1 The configuration of master-slave system

Based on studies above, a master-slave catheterisation system is constructed to assist the surgery in the operating room as shown in Figure 8. It mainly consists of three parts: a steerable catheter integrated with two magnetic sensors at its distal end, an insertion mechanism with force feedback and 3D guiding image integrated with the distal end’s shape of catheter. In the procedure of catheterisation, surgeons control the master handle to operate the mechanism, which can manipulate the catheter with the feedback of advancing force to realise pulling/pushing, bending/recovering and rotating the catheter. Meanwhile, the distal end’s shape of catheter integrated with 3D virtual vascular model can be illustrated in the guiding image, in order to provide the visual and intuitive reference information to assist the surgery. Details about 3D virtual vascular model can be found in previous research (Fu et al., 2009).

**Figure 8** The configuration of master-slave system (see online version for colours)

![Configuration of master-slave system](image)

#### 4.2 Master-slave control strategy

In this project, 3-DOF Novint Falcon controller produced by Novint Technologies, Inc. (USA) is chosen as the master handle to manipulate the insertion mechanism. In the procedure of catheterisation, the motions strategy should be adapted with the location of catheter. When the catheter lies in the aorta and aortic arch with simple and large vessels, continuous speed control need to be taken to perform rapid and large movements, but in the left subclavian (LSA) or brachiocephalic trunk (BT) with complicated and tortuous vessels, step speed control need to be taken to adjust the position of catheter slowly and slightly. Therefore, two kinds of control strategies are performed coordinately to facilitate the surgeons to position the catheter conveniently and dexterously.

1. **Continuous speed mode:** In every sampling period, the change of every DOF of Falcon controller integrated with the state of button is transformed into every motion’s velocity of the catheter. Multimedia timer is used to guarantee the precise sampling period in order to improve the positioning accuracy for the catheter.

2. **Step speed mode:** In this mode, three buttons are used to correspond three motions of catheter. When any button is pressed, the corresponding motion is operated with a pre-defined step value. So it can adjust the catheter with a slight movement to adapt the tortuous and complicated vessels.

### 5 Experimental results and discussion

Based on the developed master-slave catheterisation system, experiments are carried out to assess the property of the insertion mechanism and to validate the effectiveness of catheterisation.

#### 5.1 Experimental setup

In the procedure of intervention, the surgeons use the 3-DOF controller to operate the insertion mechanism in order to manipulate the catheter to reach the target point with the assistance of 3D guiding image. Meanwhile, the information of distal end of the catheter is displayed in the screen with the 3D vascular model in the form of four views to facilitate the operator. The thorax vascular phantom serves as the environment for catheterisation. The components are shown in Table 1.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Experimental conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Item</strong></td>
<td><strong>Condition</strong></td>
</tr>
<tr>
<td>Catheter</td>
<td>Developed pull-wire catheter with magnetic tracking sensors</td>
</tr>
<tr>
<td>Collecting device</td>
<td>NDI aurora system (Canada)</td>
</tr>
<tr>
<td>Master handle</td>
<td>3-DOF Novint Falcon controller (USA)</td>
</tr>
<tr>
<td>Slave mechanism</td>
<td>Developed insertion mechanism</td>
</tr>
<tr>
<td>Guiding image</td>
<td>Developed 3D guiding image with four views</td>
</tr>
<tr>
<td>Environment</td>
<td>Thorax vascular phantom (Canada)</td>
</tr>
</tbody>
</table>
5.2 Experiments of the insertion mechanism

To test the accuracy and stability of the insertion mechanism, three experiments are carried out to assess the operations of pulling/pushing, bending/recovering and rotating.

For the experiment of pulling/pushing, the catheter is put outside the thorax vascular phantom. The constant pulse is sent to the stepping motors in the insertion mechanism for 20 times in order to push the catheter, and then the opposite direction pulses are sent to pull the catheter back to the original point. Generally, if the catheter is supposed to be the rigid body, the relationship between the displacement and pulse number should be linear theoretically as shown in Figure 9. It is verified that the experimental values are fit for the theoretical values very well. In the procedure of pulling, the accumulated error increase with the pulse number, whose maximum absolute value is 3.47 mm in the aggregate length of 81.77 mm. In every constant pulse, the relative error is no more that 1 mm with the average value of 0.14 mm. Therefore, it is indicated that the motion of pulling/pushing has the high accuracy in the segment of artery. However, in the thorax vascular phantom such as LSA or BT where the vessels are very complicated and tortuous, the catheter can not keep the same linear property due to possible external forces.

For the experiments of rotating, the similar method is taken to test its property in the same environment. The results are shown in Figure 10. The experimental value has the same liner property with the theoretical value, whose maximum absolute accumulated error is 2.88 degrees in the aggregate degree of 234.38 degrees. In every constant pulse, the relative error is no more than 2 degrees with the average value of 0.16 degrees. Therefore, the accuracy of rotating fulfils the requirements. But in the tortuous vessels, the flexibility of catheter and external force make it impossible to conform to the linear property, so it is hard to guarantee the accuracy of catheter’s distal end in any location of vessels.

For the experiment of bending/recovering, the catheter also suspends outside of the thorax vascular phantom. Based on the circular arc supposition in equations (9) and (10), the theoretical relationship between the bending degree and pulse number pulse number is linear, which has obvious differences with the experimental results, as shown in Figure 11. In the beginning of bending and in the end of recovering, the bending degree has few changes with the non-linear property, but when the degree increases to more than 30 degrees, it has a linear proportion with the similar slope to the theoretical relationship. In the procedure of bending and recovering for several times from 1 to 7, it is obvious that the backlash non-linear exists.
5.3 Experiments of force feedback

For the surgeons, force feedback can provide more direct sense to facilitate the catheterisation. For this, three experiments are carried out to show the force information in different conditions. Here the sampling frequency of force is 50 Hz.

Figure 12 The advancing force in (a), (c), (e) and retreating force in (b), (d), (f) in different conditions (continued) (see online version for colours)
In Figures 12(a) and 12(b) represent the advancing force and retreating force respectively on condition that the friction wheel rotates freely without the catheter. The force is mainly to overcome the friction in the active friction wheel. It demonstrates that the forces are both less than 0.05 N in most cases.

Then, Figures 12(c) and 12(d) represent the forces on condition that the friction wheel rotates with the catheter clamped by the passive friction wheel. The force is sampled when the experiment is done with the catheter suspending, which stands for the friction of both active and passive friction wheel. The results show that when the catheter is pushed, the advancing force is up to about 0.3 N; when the catheter is pulled, the retreating force is up to about 0.4 N.

In Figures 12(e) and 12(f), the experiment is done in the aorta of thorax vascular phantom. The procedure is performed through three steps: pushing into the direct vessel, getting blocked by the vessel, pulling out to the direct vessel. It shows that when the catheter is blocked by the vessel and the friction wheel begins to skid, the maximum advancing force is 1.25 N and the maximum retreating force is 0.6 N.

In the procedure of intervention, when the advancing force is about 0.3–0.4 N, it indicates that the catheter is not blocked or has no collision with surrounding vessels, then surgeons could insert it with a large step to improve interventional efficacy; when the advancing force is about 1 N, it indicates that the catheter is blocked and can not be inserted, continuous insertion made by the insertion mechanism would not make any movements to the distal end of catheter, even cause puncture to the vessels, so surgeons should take the relationship of positions from 3D guiding image as reference to determinate the following operations. Therefore, force information can be integrated with image information to assist the procedure and to improve the safety. Besides, it also reduces the complexity of intervention and enables the less experienced surgeons to perform the surgery.

### 5.4 Experiments of catheterisation

Using the master-slave system, the catheterisation should be performed to evaluate its effectiveness. Due to different operators, vessels, manipulation methods and guiding images, the duration and success rate of the intervention are also different. Thus, a series of in-vitro experiments are carried out in the thorax vascular phantom by two operators in different modes: 2D guiding image manually, 3D guiding image manually and 3D guiding image with the handle. The procedure is performed from the aorta to LSA and BT for ten times, as shown in Figure 13.

The experiments above are carried out in finite thorax vascular phantom, whose results shown in Table 2 would be different with that on live animals. So the data can only present the system’s performance to a certain extent. However, based on the constructed system, the comparison between traditional catheterisation and robotic catheterisation can be made below:

<table>
<thead>
<tr>
<th>Operator</th>
<th>Result</th>
<th>2D manual</th>
<th>3D manual</th>
<th>3D handle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Success</td>
<td>31.6</td>
<td>29.4</td>
<td>60.1</td>
</tr>
<tr>
<td>2</td>
<td>Success</td>
<td>35.7</td>
<td>27.5</td>
<td>65.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operator</th>
<th>Result</th>
<th>2D manual</th>
<th>3D manual</th>
<th>3D handle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fail 5</td>
<td>234.5</td>
<td>72.2</td>
<td>135.3</td>
</tr>
<tr>
<td>2</td>
<td>Fail 7</td>
<td>252.9</td>
<td>89.7</td>
<td>142.5</td>
</tr>
</tbody>
</table>

### 6 Conclusions

This paper constructed a master-slave catheterisation system for positioning the steerable catheter. A pull-wire catheter
was developed with two magnetic tracking sensors embedded at its distal end. An insertion mechanism with force feedback was designed to assist surgeons to perform the catheterisation. Quantitative analysis was conducted to evaluate the performance of 3D guiding image and master-slave insertion mechanism by comparing the duration and success rate with different catheterisation modes. The results demonstrated that two magnetic sensors embedded at the distal end of catheter could provide the position and pose of bending segment of catheter; and the insertion mechanism could position the distal end of pull-wire catheter with high stability and accuracy. With the master-slave catheterisation system, surgeons can be left away from the operating area using the insertion mechanism to achieve the intervention, which reduces the radiation injury of x-rays and improves the safety.

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