

A Novel Trajectory Predicting Method of Catheter for the Vascular Interventional Surgical Robot

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Abstract-In the process of vascular interventional surgery, there are many factors that affect the movement of the catheter in the complex vascular environment. In order to avoid the collision between the catheter and the vascular wall, the real-time requirements for the path planning of the catheter are higher and higher. The trajectory prediction of the catheter can better solve the real-time problem. In this paper, a trajectory prediction algorithm based on Kalman filter is proposed. The optimal state value of the next time is predicted by the state value of the previous time. In this paper, the real-time trajectory of the catheter in the virtual environment is extracted by the vascular interventional surgery doctor training system. Then the predicted value is calculated by Kalman filter, and analysis the error between the predicted trajectory and the actual trajectory. The experimental results show that the trajectory predicted by Kalman filter is close to the real trajectory.

Index Terms - Avoid collision, Trajectory prediction, Real time, Kalman filter algorithm

I. INTRODUCTION

With the development of society, great changes have taken place in people's life style. Vascular disease has seriously threatened the health of contemporary people. Vascular interventional surgical has the advantages of small trauma, fast recovery and accurate intervention site. At present, it is the first choice to treat the vascular diseases. Vascular interventional surgical is a kind of surgical method which uses modern high-tech medical imaging means to obtain the image of the tissue at the lesions, and under the guidance of vascular interventional surgical instruments such as guide wire and catheter to reach the designated clinical diagnosis of the lesions along the blood vessels, and then carry out treatment on the lesions. However, in the traditional vascular interventional surgical, doctors use the physical contact method to directly operate the catheter and guide wire to the location of the lesions with their hands under the environment of X-ray radiation, which does great harm to the health of doctors and has high technical and physical requirements for doctors, so the application of vascular interventional surgical is limited. With the development of intelligent robot technology, vascular interventional surgical

robot can solve the above problems, and improve the accuracy, dexterity and safety of the operation.

Because of the complexity of the intravascular environment, doctors will face many unpredictable problems during the operation, which will bring great risks and difficulties to the operation. In general, doctors plan their paths before surgical. The path planning of vascular interventional surgical is the best path planning from the surgical approach to the lesion, avoiding the collision between the catheter and the vessel wall, reducing the operation time and effectively improving the success rate of the operation. But during the surgical, doctors will deviate from the trajectory due to their own operation problems, which will increase the risk of puncturing blood vessels. Therefore, it is necessary to predict the trajectory of the catheter during the operation. Predicting the trajectory of the catheter can detect the abnormal trajectory in advance and give an alarm. In addition, when the predicted trajectory is abnormal, the local path planning can be carried out in time. The navigation system of vascular interventional surgical mainly includes the following three functions:

1. Plan a reasonable path before the operation to prevent the collision between the catheter and the vessel wall, and at the same time reduce the operation time.
2. Monitor the catheter in real time and predict the catheter trajectory in the process of doctor's operation.
3. When the predicted trajectory is abnormal, the doctor will be warned in advance, and the local path will be planned in time.

In 2011, Hansen medical introduced Sensei (R) x robot system, which has good stability and can improve real-time force feedback [9,10]. In 2018, Corindus vascular Inc. of the United States designed the Corpath GPX system, which extends the therapeutic field [11]. In 2017, University of Ulsan, Biomedical Engineering Research Center, Asan Institute for Life Sciences and Asan Medical Center in South Korea jointly developed a novel master-slave catheter interventional surgical robot system [12]. In 2010, Nankai University and Tianjin University jointly developed the wonderful hand a surgical robot system, which is the first interventional surgical robot in China.

The safety of the navigation system can be greatly improved by adding the prediction of the catheter trajectory to the navigation system of vascular interventional operation. The innovation of this paper is that Kalman filter algorithm is used to predict the dynamic track of the catheter, and the track position of the next time is predicted by the estimated value of the previous time and the observed value of the current time. According to the prediction results, the track of the catheter can be monitored in real time and the abnormal track of the catheter can be found in advance. Because the Kalman filter algorithm can get a good track prediction effect and does not need to deal with a large number of data, it can ensure the real-time track prediction. So the Kalman filter algorithm is used in this paper.

The paper is divided into five parts. The first part introduces the robot and navigation system of vascular interventional surgical; the second part will introduces the theoretical basis of conduit trajectory prediction; the third part will carry out the Kalman filter algorithm and trajectory anomaly warning; the fourth part will experiment and analyze the predicted conduit trajectory ; the fifth part will summarize this article.

II. OVERVIEW OF TRAJECTORY PREDICTION

Vascular interventional surgical has been widely used in clinical practice, but it has high risk and complexity. Preoperative path planning and real-time monitoring of catheter trajectory can greatly improve the safety of surgical. The vessel structure is complex, so when the catheter moves in the vessel, there will be many unpredictable situations, such as improper operation of doctors, unclear medical image, etc., which will lead to the catheter deviate from the planned global path, and the abnormal path will lead to the failure of the operation. Therefore, it is necessary to predict the trajectory of the catheter and find the abnormal trajectory in time and take local path planning measures.

Catheter trajectory prediction is an important part of the navigation system of vascular interventional surgery. With the development of artificial intelligence technology, there are more and more trajectory prediction algorithms. The most commonly used trajectory prediction algorithms include Kalman filter algorithm, least square algorithm and neural network algorithm. With the development of artificial intelligence, there are many algorithms for trajectory prediction.

It is necessary to process the historical data of catheter motion and establish a prediction model to predict the trajectory of catheter using neural network algorithm. Then, the prediction error calibration module is needed to verify and correct the final prediction results. Finally, we can get a better prediction result. However, real-time is one of the factors that affect the training effect. Because the neural network algorithm needs to analyze a large number of historical data, it can not guarantee the real-time trajectory prediction.

The least square method has the advantages of small calculation amount and simple calculation. But it can not accurately predict the trajectory of moving objects. Kalman

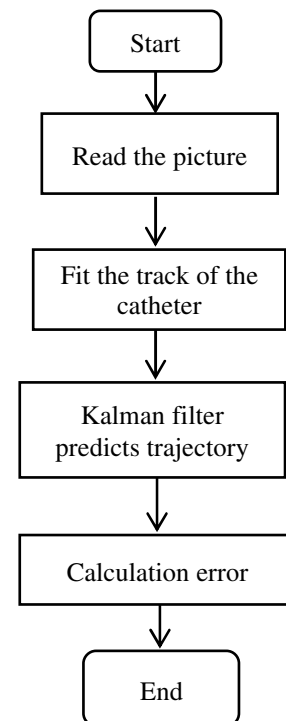


Fig 1 The steps of trajectory prediction

filtering algorithm is a common method to estimate the state value of objects. It uses the state quantity of $k-1$ time to predict the state quantity of K time, which is simple, fast and has good stability and real-time. Through the comparison of the above three methods, this paper adopts Kalman filter method to predict the trajectory of conduit.

After the global path planning and motion information of the conduit are obtained, the current and multiple time trajectories and motion information of the conduit are fitted to obtain the motion trajectories of the conduit. Then Kalman filter algorithm is used to predict the motion track of the catheter, and the error between the real track and the predicted track is calculated. The steps of trajectory prediction are shown in Fig 1. In the process of vascular intervention, when the predicted trajectory of catheter reaches a certain area in a certain time, local path planning and abnormal trajectory warning are carried out in advance to reduce the risk of operation. The value of trajectory prediction of vascular interventional surgery can not be ignored, but the current trajectory prediction accuracy is not high, there is a great development space.

III. THE TRAJECTORY PREDICTION BASED ON KALMAN FILTER ALGORITHM

A. Kalman Filter Algorithm

The traditional trajectory prediction algorithm based on fitting has low accuracy and poor real-time performance, so the dynamic trajectory prediction algorithm of Kalman filter is proposed. Kalman filter is an algorithm that uses the linear system state equation to estimate the system state optimally through the system input and output observation data. Because the observation data includes the influence of noise and interference in the system, the optimal estimation can also

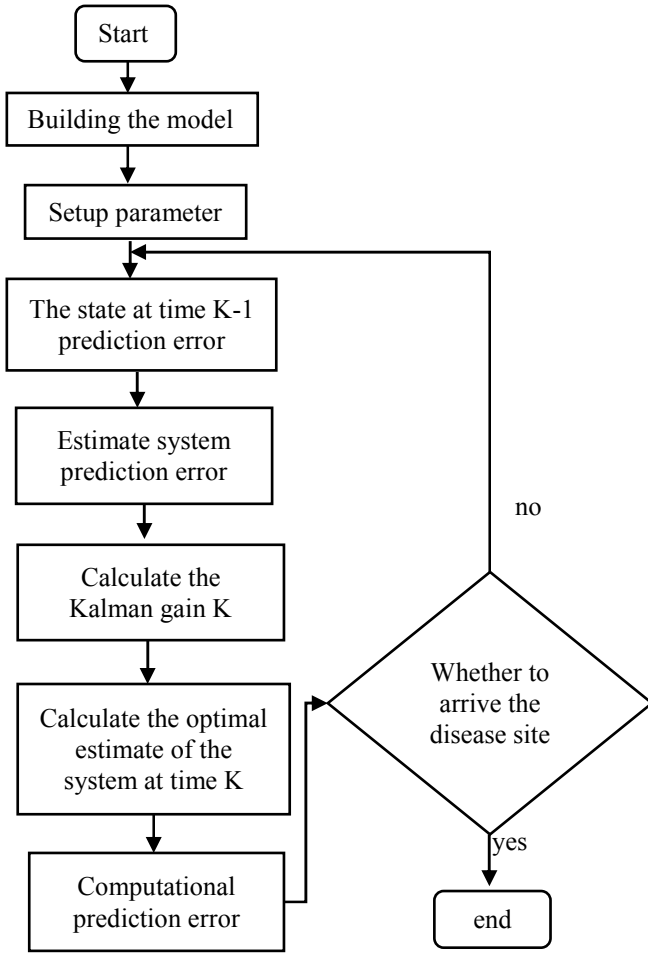


Fig 2 Flow chart of Kalman filter algorithm

be regarded as a filtering process. Kalman filter is suitable for changing and unknown problems. It only stores the state value of the last time, and occupies a small amount of memory. It can solve the real-time problem well.

Kalman filter algorithm for trajectory prediction is a recursive process, including two parts: time update and measurement update. Time update is used to calculate the predicted value of the system, including state prediction and covariance prediction. Observation update is to correct the predicted value from time update. Flow chart of Kalman filter algorithm is shown in Fig2.

This linear equation of state is known from the formula (1):

$$X_{t+1} = F_t X_t + B_t W_t \quad (1)$$

Where X_{t+1} is the state matrix of the conduit at time t+1, F_t is the state transition matrix, indicating how to predict the current state from the previous state, X_t is the state matrix of the conduit at time t, B_t is the control matrix, indicating how the noise acts on the current state, W_t is system noise.

The observation equation is shown in formula (2):

$$Y_t = H_t X_t + V_t \quad (2)$$

Where Y_t is the observation vector at time t, H represents the transformation relationship between the real state and its

observation state, V_t represents observation noise. We assume that W_t and V_t are Gaussian white noises, Q and R are covariance matrices of two kinds of noises respectively, then the autocorrelation matrix is formula (3) -(4):

$$E(W_t W_t^T) = \begin{cases} Q_t, & i = t \\ 0, & i \neq t \end{cases} \quad (3)$$

$$E(V_t V_t^T) = \begin{cases} R_t, & i = t \\ 0, & i \neq t \end{cases} \quad (4)$$

When W_t and V_t are not related, the matrix is formula (5):

$$E(W_t V_t^T) = 0 \quad (5)$$

The calculation of the minimum variance is formula (6):

$$J = E((X_t - X'_t)(X_t - X'_t)^T) \quad (6)$$

X_t represents the state value at time t, and X'_t represents the optimal state prediction value at time t.

The update equation of the current state estimated by the optimal state of the previous moment is shown in formula (7)-(8):

$$X''_{t+1} = F_t X'_t \quad (7)$$

$$Y''_{t+1} = H_t X''_{t+1} \quad (8)$$

Where X''_{t+1} is the state value at time t+1 predicted by the optimal state estimation at time t.

When the predicted trajectory value is obtained, the predicted value and the observed value use the measurement update equation to get the optimal estimation point. Equation (9)-(10) is the renewal equation of measurement.

$$D_{t+1} = Y_{t+1} - Y''_{t+1} \quad (9)$$

$$X'_{t+1} = X''_{t+1} + K_{t+1} D_{t+1} \quad (10)$$

Where K is the filter gain matrix.

The gain matrix is calculated by using the covariance of observation noise and state noise. The formula is shown in (11)-(13), Equation (14) is the covariance updating formula of the optimal state estimation at the time of t+1:

$$P''_{t+1} = F_t P'_t F_t^T + B_t \quad (11)$$

$$S_{t+1} = H_{t+1} P''_{t+1} H_{t+1}^T + R_{t+1} \quad (12)$$

$$K_{t+1} = P''_{t+1} H_{t+1}^T S_{t+1}^{-1} \quad (13)$$

$$P'_{t+1} = P''_{t+1} - K_{t+1} S_{t+1} K_{t+1}^T \quad (14)$$

Where P'_{t+1} is the error variance matrix at the time of t+1, and P''_{t+1} is the error matrix of the predicted state at the time of t+1.

The method for calculating the gain matrix K is shown in equation (15):

$$K_t = F_t P'_t H_t^T (H_t P'_t H_t^T - R_t)^{-1} \quad (15)$$

When the gain matrix K is obtained, the optimal prediction state at the next time can be obtained according to formula (16):

$$X'_{t+1} = F_t X''_t + K_t (Z_t - H_t X''_t) \quad (16)$$

The calculation of updating the estimation error variance matrix is shown in formula (17):

$$P''_{t+1} = P''_t F_t^T - F_t P''_t H_t^T [H_t P''_t H_t^T + R_t]^{-1} H_t P''_t F_t^T + B_t Q_t B_t^T \quad (17)$$

The horizontal error between the predicted trajectory and the actual trajectory is calculated according to equation (18):

$$e_x = |x_i - x'_i| \quad (18)$$

The lengthwise error between the predicted trajectory and the actual trajectory is calculated according to equation (19):

$$e_y = |y_i - y'_i| \quad (19)$$

Where e_x is the horizontal error, e_y is the lengthwise error, (x_i, y_i) is the position of the actual track point, (x'_i, y'_i) is the position of the predicted track point.

B. Kalman Filter Model

The trajectory prediction in this paper is applied in the training system of the vascular interventional surgical robot. Firstly, the motion trajectory of the catheter in the training system should be collected. Then, the motion track curve of the conduit is extracted by the fitting method. We can get the initial state value of the conduit according to the trajectory curve of the conduit. As shown in Fig. 3, the trajectory of the catheter in the training system is shown. As shown in Fig 4, the fitted conduit motion track curve.

In the training system of vascular interventional surgeons, the current velocity of catheter can be collected directly. We need to convert the current velocity v of the catheter to the speed of the X axis (v_x) and the speed of the Y axis (v_y). In the same way, the acceleration is also decomposed into x-axis and y-axis components. As shown in equation 20, it is the state value at the time of conduit k .

$$X_k = \begin{bmatrix} x_k \\ v_{xk} \\ y_k \\ v_{yk} \\ a_{xk} \\ a_{yk} \end{bmatrix} \quad (20)$$

Where x is the distance in X direction, y is the distance in Y direction, v_{xk} is the velocity in the X direction at k time, v_{yk} is the velocity in the Y direction at k time, a_{xk} is the acceleration in X direction at k time, a_{yk} is the acceleration in Y direction at k time.

The relationship between acceleration, velocity and displacement is shown in formula 21-26:

$$v_{xk} = v_{xk-1} + a_{xk-1}t \quad (21)$$

$$x_k = x_{k-1} + v_{xk-1}t + \frac{1}{2}a_{xk-1}t^2 \quad (22)$$

$$a_{xk} = a_{xk-1} \quad (23)$$

$$v_{yk} = v_{yk-1} + a_{yk-1}t \quad (24)$$

$$y_k = y_{k-1} + v_{yk-1}t + \frac{1}{2}a_{yk-1}t^2 \quad (25)$$

$$a_{yk} = a_{yk-1} \quad (26)$$

According to formula 21-26, the state transition matrix of the model is:

$$A = \begin{bmatrix} 1 & T & 0 & 0 & T^2/2 & 0 \\ 0 & 1 & 0 & 0 & T & 0 \\ 0 & 0 & 1 & T & 0 & T^2/2 \\ 0 & 0 & 0 & 1 & 0 & T \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (27)$$

Where F is the state transition matrix, T is the sampling period.

Y_t is the observation matrix of the prediction model, whose matrix is shown in formula 28:

$$Y_t = \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_k \\ v_{xk} \\ y_k \\ v_{yk} \\ a_{xk} \\ a_{yk} \end{bmatrix} \quad (28)$$

The observation matrix is shown in equation 29:

$$H = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} \quad (29)$$

By inputting the current state value of the catheter into the prediction model of the catheter, the next state value of the catheter can be calculated.

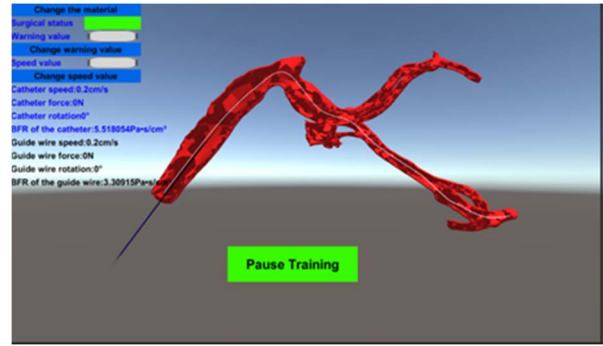


Fig 3 The trajectory of the catheter in the training system

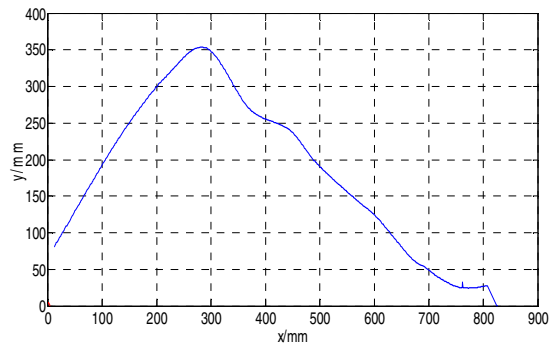
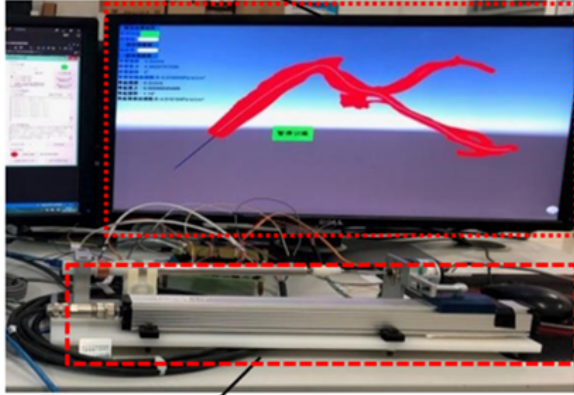


Fig 4 The fitted conduit motion track curve

Training system interface



The master manipulator with 2 degrees of freedom

Fig 5 The experimental platform

IV. EXPERIMENTAL RESULTS

A. The design of experiment

This experiment is carried out in the training system of vascular interventional surgeons in our laboratory, as shown in Figure 5. Firstly, master manipulator is connected with the training system. Then through the main end to control the virtual environment catheter in the vascular movement. Then, through the display interface of the training system, MATLAB is used to fit the actual track of the conduit and collect the state matrix of the conduit movement. Finally, the predicted trajectory of the catheter is calculated by the Kalman filter algorithm of MATLAB.

The optimal state prediction value of the next time can be obtained through the observation value prediction value of t time and the Kalman filter algorithm. The comparison between the real trajectory and the Kalman optimal prediction trajectory is shown in Fig 6. As shown in Fig 7, the comparison between the real track and predicted track of the conduit at the first turning. Where X axis represents the coordinate of conduit in horizontal direction, Y axis represents the coordinate of conduit in lengthwise direction.

According to the comparison between the real trajectory and the predicted trajectory, the predicted trajectory obtained by Kalman filter can follow the real trajectory of the conduit in real time.

B. Analysis of Experimental Results

According to the actual position and predicted position of the horizontal direction and lengthwise direction of the catheter, and calculate the difference between them to get the error of horizontal direction and lengthwise direction. As shown in Fig 8, the error in horizontal direction and the error in lengthwise direction is shown in Fig 9. In the figure, the X axis represents time, and the Y axis represents error. The maximum mean error in the horizontal direction in Fig 9 is 0.204mm. The maximum mean error of lengthwise direction in Figure 9 is 0.476mm. The position with the largest error is the position of the conduit turning. According to figure 8 and Figure 9, the error between the predicted trajectory and the

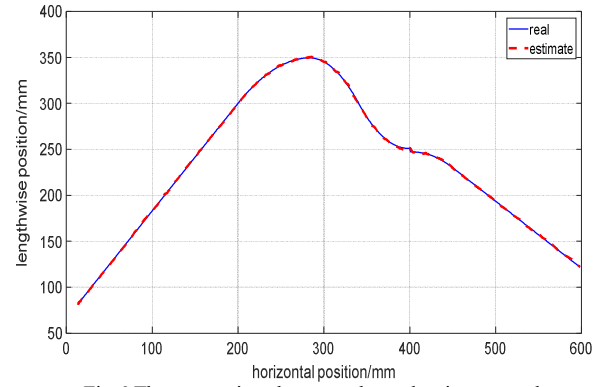


Fig 6 The comparison between the real trajectory and the Kalman optimal prediction trajectory

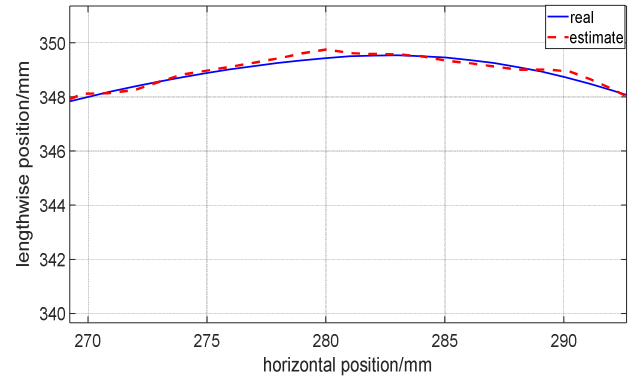


Fig 7 The comparison between the real track and predicted track of the conduit at the first turning

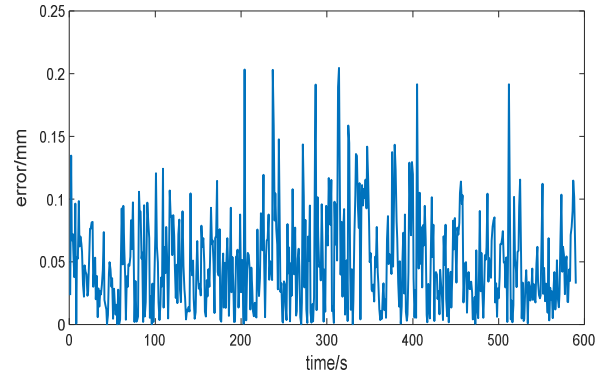


Fig 8 The error in horizontal direction

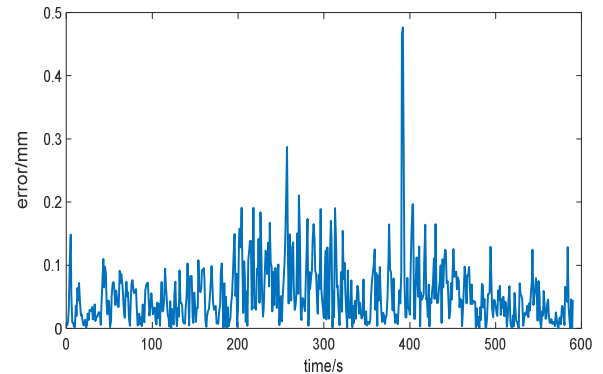


Fig 9 The error in lengthwise direction

real trajectory of the designed catheter trajectory prediction system is within 0.5mm, so the design of the catheter trajectory prediction system is effective.

The biggest error in this experiment is at the corner. Kalman filter is to predict the value of the next time according to the previous time. When the acceleration at the last moment is positive, the acceleration at the next moment is negative. Therefore, the error at the corner is the largest. Through data analysis, the maximum error of trajectory prediction by Kalman filter is within the allowable range, so this method is effective.

V. CONCLUSIONS AND FUTURE WORK

In this paper, a method based on Kalman filter is proposed to predict the trajectory of the catheter. The position of the catheter at the next time is predicted according to the state matrix of the catheter at the previous time. This method can give real-time warning to doctors, and greatly improve the safety of the operation. The experimental results show that this method can accurately predict the position of catheter in the next time. In the future, we can design a safety warning interface according to the predicted trajectory.

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REFERENCES

- [1] S. Guo, Q. Zhan, J. Guo, C. Meng, X. Jin, "Vascular Environment Modeling and Verification for The Virtual Vessel Interventional Surgery Training System", International Conference on Mechatronics and Automation, pp. 1087-1092, 2018
- [2] J. Guo, L. Qi, S. Guo, C. Meng, Q. Zhan, "Study on Tracking Stability for a Master-Slave Vascular Interventional Robotic System", International Conference on Mechatronics and Automation, pp.1387-1392, 2019
- [3] L. Zhang, S. Guo, H. Yu, Y. Song, "Performance evaluation of a strain gauge force sensor for a haptic robot-assisted catheter operating system," Microsystem Technologies, vol. 23, no. 10, pp. 5041-5050, 2017
- [4] Y. Wang, S. Guo, Y. Li, T. Tamiya, Y. Song, "Design and evaluation of safety operation VR training system for robotic catheter surgery", Medical & Biological Engineering & Computing, vol.56, no.1, pp.2535, 2017.
- [5] J. Guo, Y. Cheng, S. Guo, "Three-dimensional reconstruction of brain blood vessels and algorithm implementation", Journal of Harbin Engineering University, vol. 40, no. 4, pp. 1-6, 2019.
- [6] S. Guo, Q. Zhan, J. Guo, C. Meng, L. Qi, "A Novel Vascular Interventional Surgeon Training System with Cooperation between Catheter and Guidewire", International Conference on Mechatronics and Automation, pp.1403-1408, 2019
- [7] J. Guo, C. Meng, S. Guo, Q. Fu, Q. Zhan, L. Qi, "Design and Evaluation of a Novel Slave Manipulator for the Vascular Interventional Robotic System", International Conference on Mechatronics and Automation, pp.1350-1355, 2019
- [8] S. Guo, Y. Wang, N. Xiao, Y. Li, Y. Jiang, "Study on Real-time Force Feedback with a Master-slave Interventional Surgical Robotic System", Biomedical Microdevices, vol.20, no.2, 2018
- [9] J. Guo, S. Guo, S. Yang, "Study on Robust Control for the Vascular Interventional Surgical Robot", International Conference on Mechatronics and Automation, pp. 1361-1366, 2019
- [10] J. Guo, S. Guo, Y. Yu, "Design and Characteristics Evaluation of a Novel Teleoperated Robotic Catheterization System with Force Feedback for

- Vascular Interventional Surgery", Biomedical Microdevices, vol.18, no.5, pp.1-16, 2016
- [11] L. Zhang, S. Parrini, C. Freschi, V. Ferrari, S. Condino, M. Ferrari, D. Caramella, "3D ultrasound centerline tracking of abdominal vessels for endovascular navigation", International journal of computer assisted radiology and surgery, vol. 9, no.1, pp.127-135, 2014.
- [12] X. Bao, S. Guo, N. Xiao, Y. Li, C. Yang and Y. Jiang, "A cooperation of catheters and guidewires-based novel remote-controlled vascular interventional robot," Biomedical Microdevices, vol. 20, no. 1, pp.20, 2018.
- [13] J. Guo, S. Guo, L. Shao, P. Wang, and Q. Gao, "Design and performance evaluation of a novel robotic catheter system for vascular interventional surgery," Microsystem Technologies, vol. 22, no. 9, pp. 2167-2176, 2015.
- [14] H. Su, W. Shang, G. Li, N. Patel and G. Fischer, "An MRI-Guided Telesurgery System Using a Fabry-Perot Interferometry Force Sensor and a Pneumatic Haptic Device," Annals of Biomedical Engineering, vol. 45, No. 8, pp. 1917-1928, 2017.
- [15] C. He, S. Wang and S. Zuo, "A linear stepping slave ovascular intervention robot with variable stiffness and force sensing," International Journal of Computer Assisted Radiology and Surgery, vol. 13, no. 5, pp. 671-682, 2018.
- [16] L. Cerenelli, B. Bortolani and E. Marcelli, "Cath ROB: A Highly Compact and Versatile Remote Catheter Navigation System," Applied Bionics and Biomechanics, vol. 2017, no. 8, pp. 1-13, 2017.
- [17] Y. Thakur, D. Holdsworth and M. Drangova, "Characterization of catheter dynamics during percutaneous transluminal catheter procedures," IEEE Trans Biomed Eng, vol. 56, no. 8, pp. 2140-2143.
- [18] Y. Song, S. Guo, X. Yin, L. Zhang, Y. Wang, H. Hirata, H. Ishihara. "Design and performance evaluation of a haptic interface based on MR fluids for endovascular tele-surgery", Microsystem Technologies, pp.909-918, 2017.