Visual Servoing Robotic Auxiliary Control of Endovascular Intervention Based on Microwire Bending Energy in DSA Image

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***Abstract*— This work presents a groundbreaking auxiliary visual servoing control approach for endovascular robotic intervention surgery. We integrated it into our robot system and validated its efficacy through experiments on a vascular phantom. Results demonstrate that the proposed auxiliary control can effectively mitigates excessive bending of the microwire during the intervention process.**

I. INTRODUCTION

The unavoidable radiation environment and the need for high-precision operations pose significant challenges to endovascular intervention surgery in clinical practice. As a viable solution, an endovascular intervention robot with remote operation and precise instrument control is highly desirable. Currently, the dominant robotic systems available in the market for endovascular intervention include the CorPath robotic platform [1] and the R-One vascular intervention robot [2]. These advanced systems are engineered to cater to neurovascular intervention, coronary intervention, and peripheral vascular intervention. The design of these robots primarily involves emulating the interventionalist's dexterity in manipulating instruments, including the control of guidewire and catheter advancement, retreat, and rotation through the use of clamps and friction wheels. However, there is currently no technology available that can accurately simulate the interventionalist's analysis of digital subtraction angiography (DSA) images and provide real-time feedback on the instrument manipulation.

In endovascular intervention surgery, real-time DSA images can offer feedback on the status of the microwire tip within the vascular lumen. If excessive bending of the microwire tip is detected, the interventionalist will manipulate the microwire to retract or rotate it, in order to avoid the occurrence of vascular intimal tears caused by the wire's elasticity. The objective of this work is to develop a function that can simulate the interventionalist's feedback control of the microwire status based on real-time DSA image information during surgery, using the endovascular intervention robot system that we have designed [3].

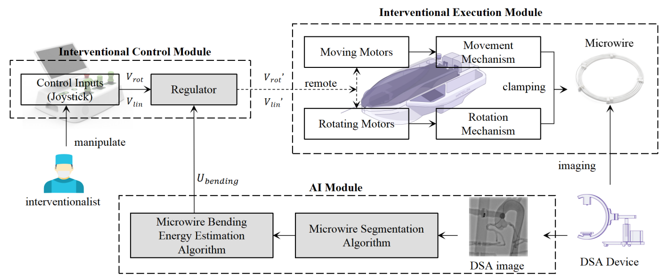

Fig. 1. The principle scheme of the vision servoing robotic auxiliary control

II. METHODOLOGY

Our endovascular intervention robot comprises three primary components, namely the intervention control module, the intervention execution module, and the AI image processing module, as shown in Fig. 1. The intervention execution module is a sophisticated motion structure consisting of clamps, friction wheels, motors, control circuits, and other components, which can enable the intervention instrument to perform various modes of motion. The intervention control module primarily consists of operating joysticks, a signal regulator, and a wireless transmission module. The interventionalist controls the microwire and balloon catheter through the joysticks while the control module sends motor speed instructions to the execution module through the wireless transmission module.

During surgery, the artificial intelligence (AI) module receives real-time DSA images as input. Initially, a deep neural network model proposed by us [4], consisting of convolutional neural networks [5] and Vision Transformer [6], is employed to segment the microwire in the image. Furthermore, we introduced a background reverse attention, which is achieved by the robust principal component analysis, into the model to eliminate a significant number of linear artifacts present in DSA images, thereby enhancing the accuracy of wire segmentation. For a given DSA image **I**, a segmented mask **S** can be obtained.

The structure of the microwire is represented by a curve that has topological continuity and can be mapped from continuous real numbers to a set of points in the 2D-plane. The segmentation result of one frame in the XRA image sequence can provide the coordinates of all foreground

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J. Zhu and C. Wang contributed equally in this work.

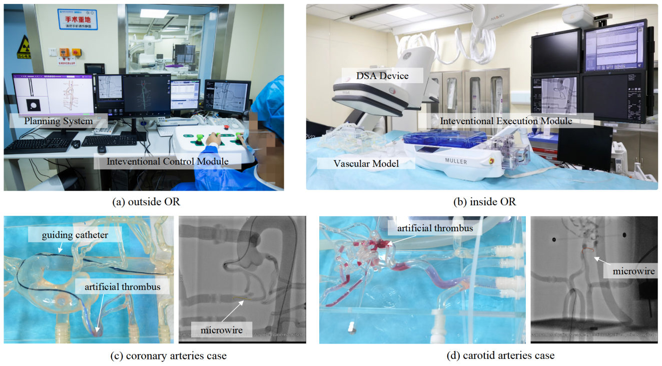

Fig. 2. The experiment setup and showcases. (a) and (b) are the experimental scenes outside and inside operation room, respectively. (c) and (d) are the showcases of coronary arteries and carotid arteries, respectively.

pixels $X = \{x_i; S_i = 1\}$, which can be used to extract the guidewire curve structure. Subsequently, the segmentation results are utilized to determine the bending energy using a simplified linear spring model that is composed of continuous connected straight rods

$$U = \sum_i U(i) = \sum_i \frac{1}{2} c \theta_i^2 \quad (1)$$

where c is the spring constant of wire, and θ is the angle between two connected rods, namely the spring strain.

This energy value is then transmitted to the regulator in the intervention control module, which adjusts the rotation speed v_{rot} and linear speed v_{lin} by the joysticks based on the energy value U to mitigate the occurrence of excessive bending energy. We used the modified sigmoid function $f(U) = 100/(1 + e^{(200-U)/10})$ to non-linearly transfer the energy to the encoding value of motor speed with range [0, 100]. The regulated rotation speed v'_{rot} and linear speed v'_{lin} can be formulated as follow,

$$v'_{rot} = \min(v_{max}, v_{rot} + f(U)), v'_{lin} = v_{lin} - f(U) \quad (2)$$

where v_{max} denotes the max encoding value of motor speed.

III. Experiments and Results

We have established an endovascular intervention robot test platform (Fig. 2) in the DSA operating room of Zhuhai People's Hospital, using a life-size vascular model as our test object. The hollow model is filled with water to simulate blood circulation, and artificial thrombus is injected into the vessels to simulate vascular atherosclerosis. To establish the main pathway, we utilize a 6F guiding catheter and a 0.035-inch angiographic guidewire, while a 0.014-inch microwire and balloon catheter are employed to pass the lesion area.

The robot operator is an interventionalist with clinical experience in vascular intervention, mainly manipulating the joysticks to pass the microwire through the lesion vessel segment. We conducted experiments on the coronary arteries and carotid arteries, and set up control experiments with the same number of open and closed auxiliary controls. We recorded the changes in the bending energy of the microwires for 50 repeated trials for each vessel. The statistical results

TABLE I

Statistical results of microwire bending energy in experiments

	auxiliary control close		auxiliary control open	
	coronary arteries	carotid arteries	coronary arteries	carotid arteries
numbers of trials	50	50	50	50
U_{max} max	362.0	354.0	100.4	93.9
U_{max} mean	170.8	235.9	60.8	56.2
U_{max} min	89.0	100.5	20.0	20.0
average time (s)	8.75	8.25	8.75	9.0

of microwire bending energy was presented in Table 1, in which the max bending energy in one trial is used to judge the effect of auxiliary control. According to the statistical results, the assisted control function significantly suppressed the bending energy of the microwires during the process of operating the microwire through the lesion area, reducing the maximum bending energy by 71.2% and keeping the passing time almost unchanged.

IV. Discussion and Conclusions

The experimental results have demonstrated that the visual servoing function can effectively mitigate the issue of excessive bending of microwire. This auxiliary control, accomplished by regulating the operator's control, may not be as efficacious for experienced interventionists as it is for their novice counterparts. Nevertheless, the significance of this work lies in the simulation of the visual feedback and hand control mechanism of interventionists during DSA for the first time. Moreover, this technology can be integrated with automatic control or reinforcement learning to realize robot autonomy.

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