Proceedings of 2021 IEEE
International Conference on Mechatronics and Automation
August 8 - 11, Takamatsu, Japan

A Novel Tremor Suppression Method for Endovascular Interventional Robotic Systems

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***Abstract* – With the development and popularization of interventional vascular surgery, various of endovascular interventional robots are rising. For safety property of master-slave interventional robotic system, operational hand tremor has a serious impact on success rate and accuracy of the robot-assisted surgery. This paper proposes a novel method based on active restraint and passive modification for tremor suppression in robot-assisted system. Hand tremor can be restricted to a allowable safe operation range by active restraint part. Then, a hybrid filtering strategy consisted of median average filter, amplitude limiter filter and exponential smoothing filter is used to reduce sampling bias and improve signal interference in passive modification part. The simulation results and comparative experiments indicate that the proposed method is capable of suppressing hand tremor effectively for burst tremor and regular tremor under the operation of surgeon. In addition, the proposed method is also instructive for the mechanical suppression produced by connected components in slave side.**

***Index Terms* – Tremor suppression, Active restraint, Passive modification, Endovascular interventional robotic system.**

I. INTRODUCTION

Recent years, vascular interventional surgery (VIS) is developing very rocket by the efforts of many researchers in the world [1]-[2]. Most of endovascular interventional robots are master-slave teleoperation systems [3]-[5], which can liberate surgeons while using the stability of robots to improve safety of operation. In addition, the most interesting advantage of endovascular interventional robots is radiation-preventing. In 2009, American Hansen Medical Company developed a set of vascular interventional surgery robot system named Sensei X. This robot passed FDA certification and launched to the market at the same year. The corporation of Corindus Vascular Robotics invented a vascular surgery machine called CorPath 200 robot system. This company went a further step that developed a new CorPath GRX robot system to improve the work process and increase the accuracy in 2016. In our previous study [6]- [7], several novel VIS systems were designed to control catheters and provide force feedback to improve operational experience of surgeons.

Hand tremor is a physiological or unconscious jitter behavior due to increasing age, long-term work load and high mental stress of operators. Tremor could affect the accuracy of motion signal and surgery safety [8]. Therefore, the research about tremor suppression is pretty important and far-reaching.

Focus on the development of hand tremor suppression in recent period, Wang Kundong et al [9] had designed a new VIS robot with multi-manipulation operation. In particular, this design could satisfy the doctor's operating habits better for reducing operating errors without any independent tremor algorithm research. A physiological tremor recognition algorithm based on means of support vector machine is proposed to distinguish surgical hand operation and normal physiological tremor by Rui Shen et al [10]. The safety of surgical process and the success rate of surgeon operation will be improved. Lingling Zheng et al [11] creatively use Magnetorheological (MR) fluids to generate force feedback for surgeons and produce resistance to the operation tremors simultaneously. This method can increase the safety and efficiency of VIS. Besides, an optimal digital filtering for tremor suppression is developed to improve the motor function in physiological medical treatment field [12]. This application stems from a need to minimize unwanted movements exhibited by people with movement disorders and the unwanted movement as a distortion which be eliminated from the intermediate signal by a digital filter.

However, recent existing studies have focused on the identification and classify about various types of tremors in VIS system. The effect of burst tremor suppression is not ideal enough for a safety operation. Additionally, the method by changing different viscosity of the MR fluid to reduce tremor is very hard to control due to non-linear material viscosity change and uneven magnetic field distribution. To address these issues, a novel tremor suppression method based on active restraint and passive modification is presented to improve the accuracy of operating date in master side. Then, these operating data after processing will be used to control the movement of slave side. The active restraint part can restrict safe operating range of operators. Correspondingly, the passive modification part based on a hybrid filtering strategy can achieve filter and improvement of motion signal. The remaining writing parts of this paper is shown as follows: the introduction of endovascular interventional robotic system is exhibited in Section II. Then, the novel method for tremor suppression consisted of active restraint and passive modification is presented in Section III. Experimental results and analysis are revealed in Section IV. At last, conclusion and future work are introduced in Section V.

II. Endovascular Interventional Robotic System

A. Overview

Fig.1 depicts the conceptual diagram of the VIS robotic system. This VIS system [13]-[15] includes two main sections: master side and slave side. The communication and control units are integrated in their respective sections to save space which is an ideal situation.

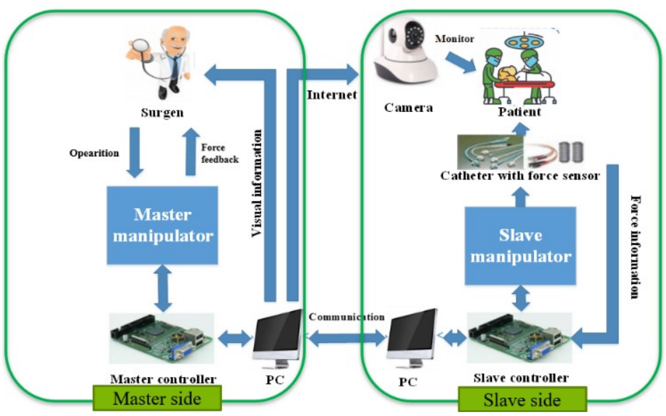


Fig. 1 Conceptual diagram of the VIS robotic system.

The master-slave endovascular interventional robotic system presented by previous research of our team is showed in Fig.2.

The device of master [15]-[17] is responsible for providing moving and rotation data of catheters and giving the force feedback to operators. The information of linear moving and

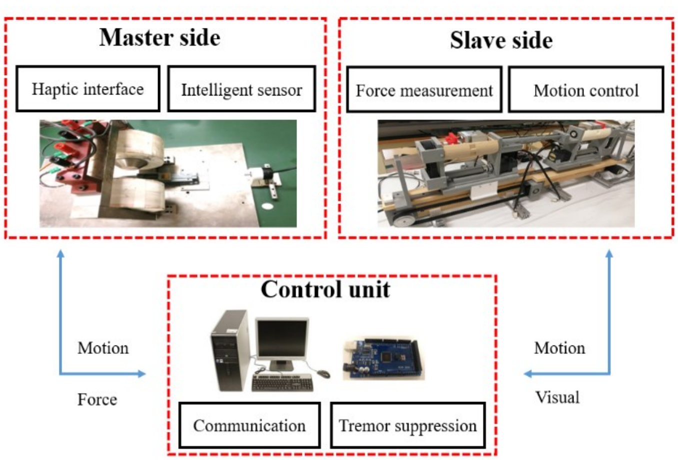


Fig. 2 Overview of the VIS robotic system.

rotational motion in master side is measured by intelligent motion sensor. MR fluid can provide the real force feedback for surgeons to improve the operational safety.

The slave side is located in the operating room which will directly contact with the patient. The movement information is measured in master side and delivered to guidewires and catheters. This part clamps catheters to achieve flexible rotational motion or advance/retreat moving. Meanwhile, force signal can be detected in this side to improve the safety of surgery.

Signal processing from both of sides and data interacting are realized by control unit [17]-[18]. Information interactions between doctors, robots and patients are realized through the wide-area network (WAN). Moreover, the novel tremor suppression method can be used in control unit to improve the accuracy of moving data transmitted from master side to slave side which is very important for the safety of robotic system.

III. Tremor Suppression Method

The moving information of operators in master side will be collected by intelligent sensors when the robotic system is conducting a surgery. The slave side will replicate surgeon's action by input of motion data captured in master manipulator. However, physiological tremors or unconscious tremors always appear during a surgery of doctor. To address this problem, a tremor suppression method based on active restraint and passive modification is designed exhibited in this section.

A. Active restraint

VIS has different manipulations and treatment strategies in different lesion conditions. During actual surgery of the master manipulator, manipulation and strength of operators will affect the moving data which be used as input in slave side. Active restraint is proposed to limit operator's behavior according to the priori rule before starting surgery.

The frequency of tremor signal is mainly distributed in the frequency band of 8~12Hz with a smaller amplitude [11]. Tremor signal usually can be approximated as a cosine curve. It is worth noting that the desired signal frequency is controlled within 2 Hz. This priori rule can be used to restraint regular hand tremor based on an active pruning function $y(t)$. This part will be the first step for operation data collected in master side. The speed signal $v(t)$ and the tremor signal $x(t)$ with corresponding frequency $f(t)$ is collected in time domain. At the beginning, operating speed should be limited in a suitable range to ensure operational safety and signal stability. If the speed is too fast, there will be a risk of puncturing blood vessel, even lead to the loss of tremor signal. Then, pruning function $y(t)$ was defined as

$$y(t) = \begin{cases} x(t) + \theta_1[f(t) - a_2] & f(t) > a_2 \\ x(t) & a_1 < f(t) < a_2 \\ x(t) + \theta_2[a_1 - f(t)] & f(t) < a_1 \end{cases} \quad (1)$$

where θ_1 and θ_2 are penalty factors. The parameter a_1 is upper limit of tremor frequency and a_2 is lower limit of tremor frequency. Choose an appropriate threshold, the tremors with regular frequency will be obtained. Through this pruning function $y(t)$, the tremors with too high frequency or too low frequency will be removed.

B. Passive modification

After the active restraint part initially, tremor signal should to make further corrections by the second part which is named passive modification. Considering surgeons conduct surgeries without any tremor which is a desired situation. The horizontal motion signal F_{v0} can be defined as

$$F_{v0} = F_n \cos\omega t \quad (2)$$

where F_n is the amplitude of normal harmonic motion. ω is the corresponding frequency. T_v is an occasional vibration force in the horizontal orientation. Force model for tremor during operation is shown in Fig.3.

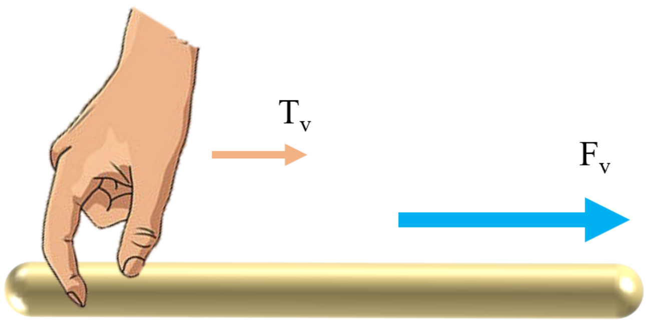


Fig. 3 Force model for the tremor during operation.

The actual vibration signal with tremor in horizontal orientation is

$$F_v = F_n \cos\omega t(1 + \cos\theta) \quad (3)$$

where θ is rotation angle refer to the horizontal direction. The actual vibration signal consists of normal horizontal motion signal and occasional vibration signal. Then, a hybrid filtering strategy is used to do correction works in this part. Three different filters act on the sampled signals in turn which is processed by active restraint part.

Firstly, median average filtering is used as a preprocessing process to embrace a regular average tremor sampled signal. The process of this filter includes continuously sampling N data, removing the maximum value and the minimum value in this queue. At after, an average sample signal S_a will be obtained by calculating arithmetic average of $N-2$ remaining data. The value of N usually is a positive integer from 5 to 14, and it is 10 in here. The goal of this preprocessing process is to get a more accurate median data which is not interfered by burst signals.

Secondly, amplitude limiter filter is adopted to judge whether the new value of vibration signal with tremor is reasonable. Overcoming the signal interference caused by accidental factors is greatest advantage of this filter. The detailed process includes two steps. Above all, determining the maximum allowable deviation of sampling A according to absolute value between the repeated experiment value and

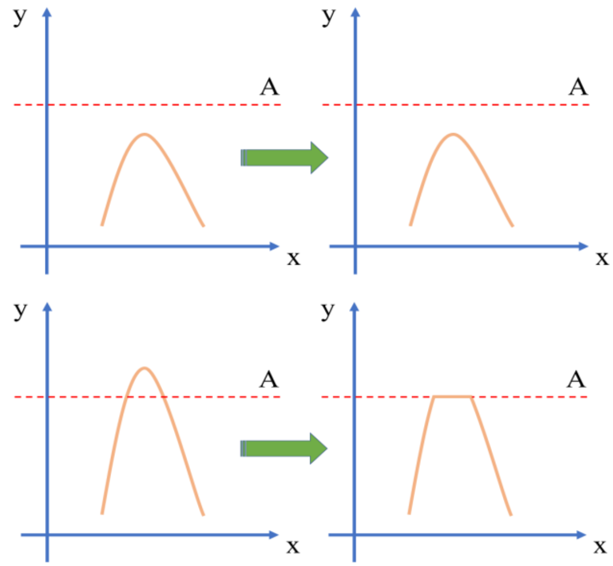


Fig. 4 Mathematical model of amplitude limiter filter.

average sample signal S_a. Executing program judgment is to complete the filter of effective sampled signals. Mathematical model of amplitude limiter filter is shown in Fig. 4.

Thirdly, exponential smoothing filter is used for signal smoothing in the final stage. The notable feature about exponential smoothing filter is that weight exponentially decays with a fixed weight over time. The formula for signal changed with time is defined as follows

$$p_t = \omega_0 \times x_t + (1 - \omega_0) \times p_{t-1} \quad (4)$$

$$p_{t-1} = \omega_0 \times x_{t-1} + (1 - \omega_0) \times p_{t-2} \quad (5)$$

where p_t represents predictive value. ω_0 is decay weight whose general value is 0.95. x_t is sample value (Here is processed value after amplitude limiter filter). If the target has fluctuate in actual scene, a smoother signal will be obtained by exponential smoothing filter. In addition, signal hysteresis will be suppressed well by this filter.

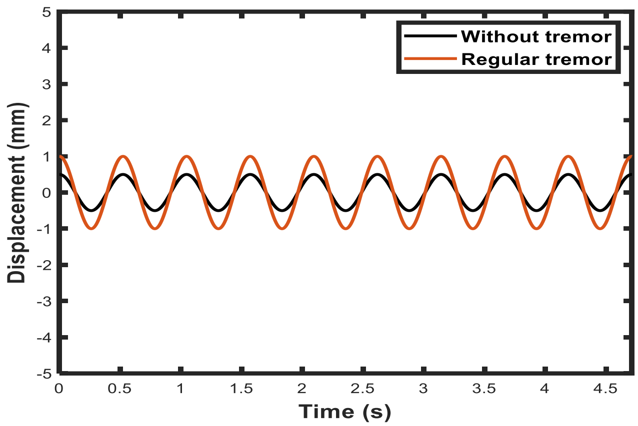
This hybrid filtering strategy combines different advantages of several filters to improve the accuracy of motion data collected in master side. By this method, motion signal with tremor will be well improved. Signals with excessive frequency and larger amplitude will be removed by the activity of multiple filters. Then, the processed signal will be used for the motion of slave side to improve the safety of surgery.

IV. Experimental Results and Analysis

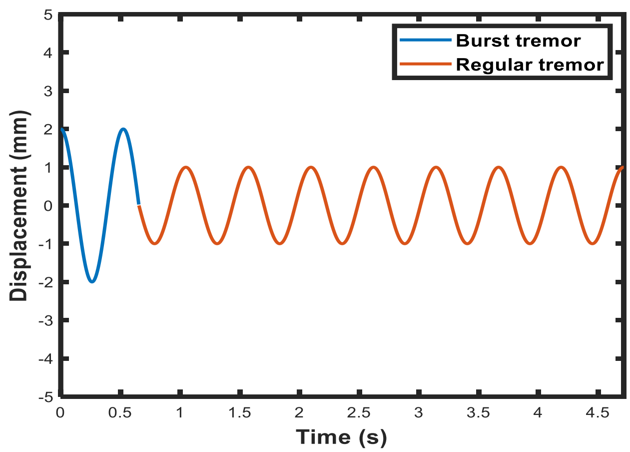
In order to verify the performance of this proposed method, MATLAB simulations and experiments are both implemented. On the one hand, simulation results can qualitatively show the feasibility of this method. On the other hand, experiment studies conducted in this section can display the performance intuitively. Moreover, the analysis of this novel method is discussed at the end of this section.

A. Simulations

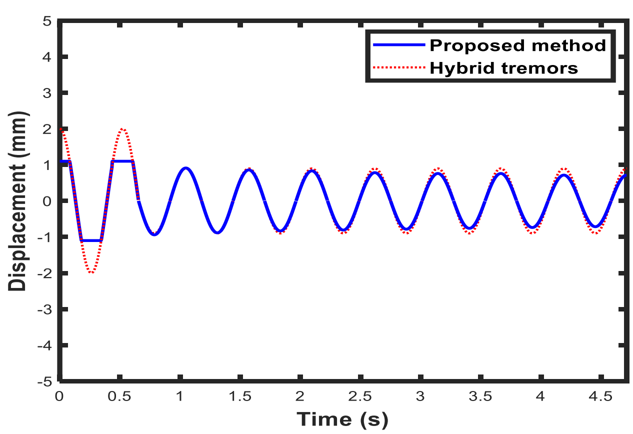
Since inevitable hand tremor and even unnatural jitter of machine, the actual motion signal detected by displacement equipment always has interferences of varying degrees. Therefore, the presence or absence of tremor and the amplitude of tremor will affect accuracy of motion signal. In this simulation part, the motion signal without any tremor is supposed to a cosine wave. Meanwhile, the results of signal simulation with tremor are given in Fig. 5.



(a) Simulation signal of regular tremor and without tremor



(b) Simulation signal of burst tremor and regular tremor



(c) Result for hybrid tremors

Fig. 5 Results of simulation for the proposed method

Fig. 5 shows the result of simulation with hybrid tremors which consisted of burst tremor and regular tremor. In this part, motion signal without tremor considered as cosine wave shown in black line. Regular tremor is also a cosine signal with a larger amplitude. Burst tremor is a sort of strong interference by the sharp wave in a short time which is depicted in Fig. 5 (b).

B. Experiments

For further test the performance of the proposed method in endovascular interventional robotic system, operations with and without this method by turn. By recording the actual position reached by guide wire tip to prove the effectiveness of our method. Firstly, recording the position of guide wire tip when operating handle works in the natural regular tremor. Then, handle produce an appropriate burst tremor by hand. Finally, monitoring the position of guide wire within proposed method. All experiments should keep a gentle speed and conduct an amplified signal due to too small signal will observe hardly for experimental results which are showed in Fig. 6.

Regular tremor

Burst tremor

Proposed method

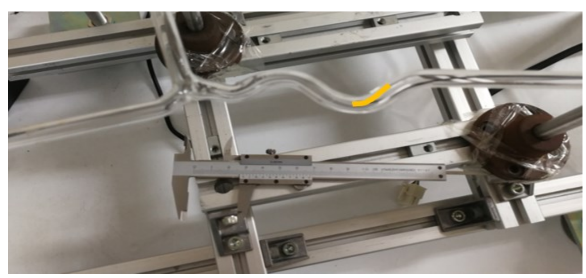


Fig. 6 Results of experiments at a certain moment

C. Discussion

The performance of proposed method is verified by both simulations and experiments showed in Fig. 5 and Fig. 6. For the reason of operations exist many unknown factors of tremor, the research for tremor suppression has a pivotal role in robotic system. The tremor suppression rate TSR is defined as follows:

$$TSR = 1 - \frac{A_S}{A_R} \tag{6}$$

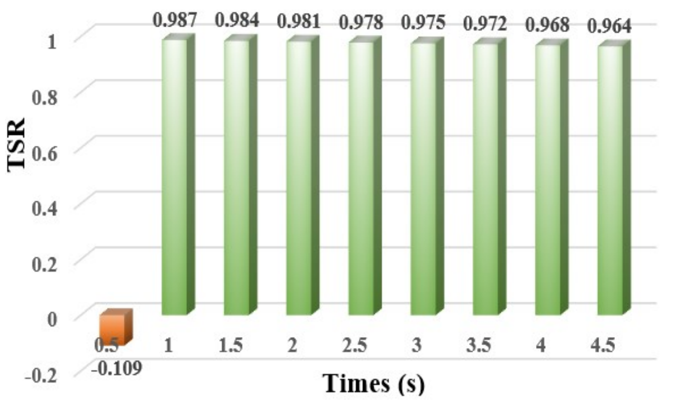


Fig. 7 Results of TSR for tremor suppression method

where A_S is the amplitude of tremor with suppression method, and A_R means the amplitude of tremor with regular interference. The results of TSR in different moments are showed in Fig. 7.

The TSR is a negative value at time 0.5s, because the amplitude after processing is higher than the amplitude of regular. When the burst signal disappears, the TSR keep a declining trend over time due to the exponential smoothing filter with a certain attenuation rate. The values of TSR are all above 0.9 after 1s. Analyzing the data of TSR in Fig. 7, the proposed method can effectively suppress tremor conclude regular tremor and burst tremor at a certain degree. In addition, the proposed method for tremor suppression is also inspirational for the mechanical tremor generated by connected components in slave side.

V. Conclusion and Future Work

In this paper, a novel tremor suppression method based on active restraint and passive modification was proposed for tremor reduction in endovascular interventional robotic systems. Combining median average filter, amplitude limiter filter and exponential smoothing filter creatively to process the signal with burst tremor and regular tremor. The performance of proposed method is evaluated by simulations and experiments. Results of the TSR indicate that the proposed method can suppress regular tremor even burst tremor effectively in the robot-assisted system. Moreover, the VIS robotic system with the proposed tremor suppression method can both improve the safety and accuracy for operators when they conduct an interventional surgery. However, collecting different amplitude and different frequency tremors are still tremendous challenges for endovascular interventional robotic system. In the future, more accurate equipment for detecting tremors and faster real-time suppression algorithms should be taken into consideration.

Acknowledgment

This work was supported in part by the National High-tech Research and Development Program (863 Program) of China under Grant 2015AA043202, and in part by SPS KAKENHI under Grant 15K2120.

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