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Study on physiological tremor recognition algorithm in the vascular interventional surgical robot

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***Abstract* - With the development of surgical robotic technology, more and more requirements on safety property were raised upon the surgical robots. For master-slave control surgical robots, it's physiological hand tremor that influences the accuracy and success rate of the robot-assisted surgery. Focusing on the physiological tremor recognition and cancelling, this paper proposes a moving-window-least-square-support-vector-machine-based recognition algorithm and adaptive filter method to rectify the wrong operations caused by physiological tremor. The performance assessment was shown with the indicator of accuracy, which implies that the MWLSSVMAF reduces accuracy error of the tremor signal. The comparison between recognition results and surface electromyographic signal is conducted for assessing the classification accuracy rate. Also, some experiments on correction effects are carried out. The results indicate that the method proposed by our research possesses better classifying accuracy rate of 83% and that the secure property requests of vascular interventional surgical robot have been improved obviously.**

Index Terms – Vascular Intervention Surgical Robot (VISR), Least Square Support Vector Machine (LS-SVM), Physiological Tremor, Tremor Recognition Algorithm, Mass-spring-damping Model.

I. INTRODUCTION

These years, researches on vascular interventional surgical robots have developed rapidly, in which surgeons are released from the risks of over-exposure to the radiation and heavy radiation-shielded garments [1]. Hence, four main commercial VIRs have been designed which are the Corpath robot system developed by Corindus Vascular Robotics [2], the Sensei and Magellan robot system designed by Hansen Medical [3], [4], the Amigo robot system invented by Catheter Robotic Inc. [5] and the Niobe robot system developed by Stereotaxis Inc. [6]. Meanwhile, many research groups have studied VISRs and such studies have been published after 2010 [7]-[11]. In our previous study, several novel VISRs were developed to operate catheters with two DOFs which can measure the proximal force and accurately realize the force feedback from the aspects of safety [12]-[15]. From the aspects of the security of the robot-assisted surgery, the controlling algorithm was designed [16], [17], remote-control communication was studied based on the Vascular Interventional Surgical Robot (VISR) [18], and collision detection was adopted for safety warning [19]

For aforementioned researches, all the robotic systems utilizes master-slave controlling method. However, long-time operation of surgeons' work, according to medical researches, would cause the hand tremor of master side which will influence the efficiency and successful rate of the surgery [20].

Tremor defined as an involuntary, rhythmic, oscillatory movement of a body part [21] is classified as action-tremor and rest-tremor from the perspectives of activation classification [22].

Considering the impacts of physiological tremor, several groups devoted their efforts to suppress it in the surgical robots. In reference [23], a surgical robotic device was designed by a research group of Johns Hopkins University, Nanyang Institute of Technology and Carnegie Mellon University, for microsurgery, which consists of sensing module, filtering module with low-pass filter and operating module to correct operator wrong motion. Meanwhile, such instrument has been applied in real microsurgery and possesses a filtering rate of 50%. However, such algorithm adopted in this research is too simple to filter the tremor signal. Another team applied a bandlimited multiple Fourier linear combiner (BMFLC) algorithm for real time estimation of the operator's physiological tremor [24]. But some tremor signals and involuntary noise of accelerometers have the same bandwidth. For tremor suppression time delay, a team of Tianjin Polytechnic University proposed a zero phase adaptive fuzzy Kalman filter in reference [25]. Nevertheless, the adopted filter can only maintain the master side and the slave-side device still vibrates. From the aspects of tremor signal analysis, although, the empirical mode decomposition-based filter was developed for fatigue induced hand tremor in laparoscopic manipulation [26] and autoregressive (AR) model was designed for physiological tremor estimation [27]. The characteristics of physiological hand tremor haven't been discovered and fully utilized in the tremor suppression system. The AR model and EMP-based filter increases the complicity of the controlling system, in which time-delay would occur.

Although these approaches have partly solved tremor suppression problems, there are still some troubles to solve as follows:

1) The algorithm can only classify tremor signals offline;
2) The approaches proposed, which adopts complex computation, introduce time delay to the system;

To address these problems, this paper proposes a Least Square-Support Vector Machine (LS-SVM) based recognition algorithm and establishes an MCK model to rectify wrong operation caused by physiological tremor. Section II will focuses on the materials and theory applied in this research. Then, the experimental setups are described in the Section III . The results are discussed by Section IV later and finally our conclusions are given in Section V.

II. Method and Materials

Use either SI (MKS) or CGS as primary units. (SI units are encouraged.) English units may be used as secondary units (in parentheses). An exception would be the use of English units as identifiers in trade, such as "3.5-inch disk drive."

A. The VISR Platform

The VISR system was designed as a remote-control master-slave robotic system, which provides precise force feedback from the slave side [28]-[31], consisting of a master device, central controller and a slave instrument. The master-side and slave-side parts work together to manipulate the catheter and the guide wire. The master side of the system utilizes a force feedback interference instrument. Such instrument, which offers virtual haptic feedback to the operator, transforms 3D coordinates and the force value of operator's hand to the central controller. The slave instrument replicates the motion of the surgeon and measures the force of catheter/guide wire. During this process, the force feedback is transmitted from the slave instrument to the master device. A conceptual schema of the system, in which the operation process and interactions of three components are presented, is shown in Fig. 1.

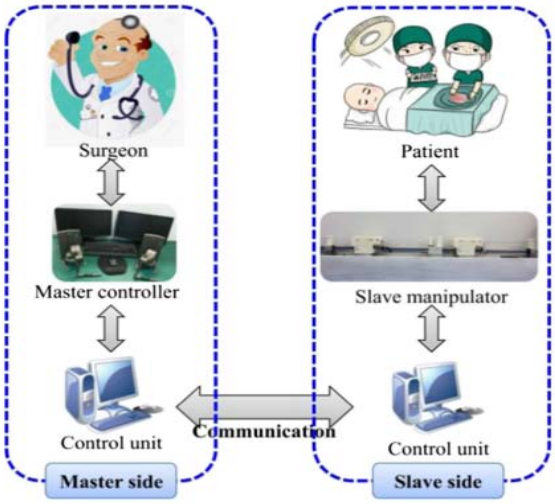

Fig. 1. Schema diagram of the VISR system.

Based on the primary version of VISR [32], a cooperation of catheters and guidewires was proposed to imitate the operations of surgeons' hands, under which the catheters and guidewires are operated by the catheter controlling unit and the guidewire controlling unit [33], [34]. To handle the cooperation of catheters and guidewires, two commercial haptic devices (Geomagic® TouchTMX, 3D Systems, Inc., USA), which is shown in Fig. 2, are applied as catheter and guidewire haptic devices in the master side. For the slave instrument as shown in Fig. 3, a linear motion platform was designed from the aspect of security of the whole system. Such design of slave platform simplifies the 3D motion into 1D motion, in which the incorrect manipulations of surgeons' hands on master devices in other 2 directions are left out.

Fig. 2. Master manipulation device of the VISR.

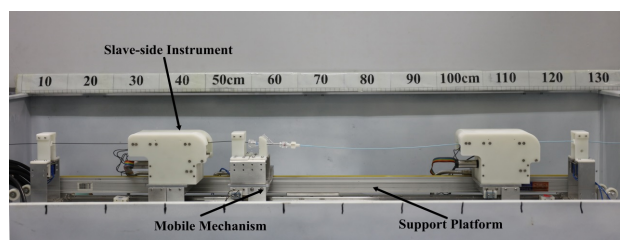

Fig. 3. A linear motion platform in slave side.

For usual surgical robotic experiments, there are blood vessel models applied for evaluation of the performance of the master-slave robotic system. And for our research, a human blood vessel model is adopted to mimic the real surgical situation and to obtain realistic moving data of surgical operation when tremor happens. And the human blood vessel model is shown as Fig. 4.

Fig. 4. The human blood vessel model for experiments.

B. *Moving Window LS-SVM (MWLSSVM)*

LS-SVM is the least squares version of support vector machines (SVM). Optimal solution with LS-SVM is obtained directly by solving a set of linear equations rather than a convex quadratic program. Moreover, computational complexity of LS-SVM is less compared to SVM because of this reformulation. The regression model of N samples for LS-SVM is:

$$y = w^T \varphi(x) + b \tag{1}$$

And in LS-SVM, the optimization problem for the function estimation is defined as follows:

$$\min_{w,b,e} J(w,e) = \frac{1}{2} w^T w + C \sum_{i=1}^{N} e_i^2 \tag{2}$$

The corresponding Lagrangian function for optimization problem is defined as

$$L(w,b,e;\alpha) = J(w,e) - \sum_{i=1}^{N} \alpha_i w^T \varphi(x_i) + b + e_i - n_i \tag{3}$$

with the Lagrangian multipliers $\alpha_i \in \Re, i = 1,2,\cdots,N$.

After eliminating e_i and w from the Karush-Kuhun-Tucker (KKT) [35] conditions for optimality obtained from (3), the solution is obtained as:

$$\delta_N = \psi_N^{-1} y_N. \tag{4}$$

In this work, the Kernel function which is RBF Kernel function is employed, $K(x,x_i) = \exp\{-\frac{\| x - x_i \|}{\sigma^2}\}$.

From (1) and (4), the prediction model with LS-SVM is obtained as

$$\hat{y}(k+T) = \sum_{i=1}^{N} \alpha_i K(x_i, x_k) + b; k = N+1, \cdots, l. \tag{5}$$

where b and α are from δ_N , equ. (4) and l is the length of test signal.

For online training of LS-SVM, whenever a new sample arrives, the trained offline is updated by incrementing the training set and decreasing the oldest samples, which is shown as Fig. 5. For incremental algorithm, the incremented training set is given by

$$\delta_{N+1} = \psi_{N+1}^{-1} y_{N+1}. \tag{6}$$

And for decremental algorithm, without explicitly calculating the matrix inversion for the N data pairs, the update rule was obtained in (6) as

$$\psi_{ij} = \psi_{ij} - \frac{\psi_{ik}\psi_{kj}}{\psi_{kk}}. \tag{7}$$

To perform the multi-step prediction of physiological tremor with MWLSSVM, consider N samples of tremor data to form a training set. Algorithmic representation for the procedure employed fot predicting tremor by updating the training set at each instant of time with MWLSSVM is provided in Algorithm 1.

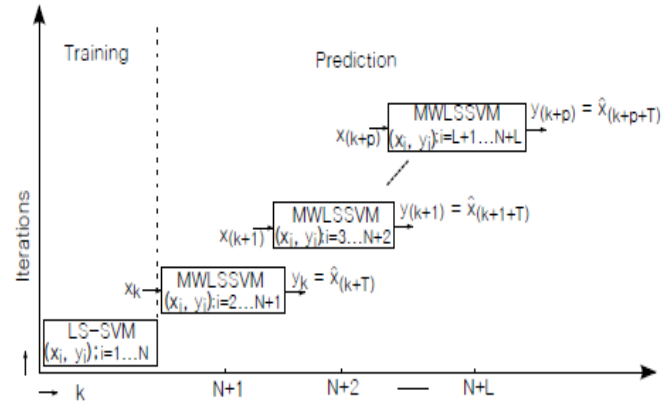

Fig. 5. Block diagram representation for tremor prediction with MWLSSVM.

Algorithm 1: MWLSSVM for tremor prediction.

Initialize: Number of training sets (N), Constant (C), Kernel variance (σ^2) and Number of samples ahead prediction (T)
Offline training: Solve (4), store Ψ_N^{-1}.
while *when a new sample arrives* **do**
  Incremental algorithm:
  increment the trained LS-SVM training set;
  compute Ψ_{N+1}^{-1} with (6);
  Decremental algorithm:
  discard the oldest sample in training set;
  compute new Ψ_N^{-1} from (8);
  Prediction:
  update the parameters, Lagrangian multipliers and bias from (4);
  perform tremor prediction with (5);
end

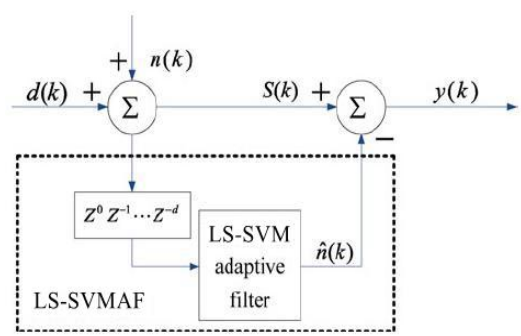

Fig. 6. Mathematical model of the proposed MWLSSVM

C. *The Theory of LSSVMAF*

In order to realize adaptive filtering of tremor signals, a mathematical model is established to cancel tremor signal briefly and clearly. As shown in Fig. 6, d(k) is a desired operation signal, which is corrupted by a tremor signal n(k). the estimation value of n(k) id denoted as $\hat{n}(k)$. the primary signal s(k) includes the desired signal d(k) and the tremor signal n(k), which is presented as

$$s(k) = d(k) + n(k). \tag{8}$$

According to $\hat{n}(k)$ and s(k), y(k) can be attained:

$$y(k) = s(k) - \hat{n}(k) = d(k) + n(k) - \hat{n}(k). \tag{9}$$

From the formulation (9), it can be concluded that the hand tremor can be cancelled completely when n(k) = $\hat{n}(k)$, that is y(k) = d(k). Thus, a novel adaptive filter based on MWLSSVM is presented to overcome the hand tremor.

III. Experiments, Results and Discussion

In this section, we first describe the experimental setups of recognition experiments and evaluation experiments. Later, performance analysis for MWLSSVM and LS-SVM is discussed. Then, the comparison results between the movement records and sEMG records are demonstrated.

A. Setups of Recognition Experiment

For physiological tremor signal sampling during the surgical situation, a blood vessel model is adopted which has been shown in Fig. 4. In this research, 10 volunteers were recruited for surgical operation of linearly pushing the catheter/ guide wire within 100 mm in the aorta and fixed rotating the catheter/ guide wire at the carotid bifurcation, which are shown in Fig. 7. The sampling frequency is 250Hz and each volunteer is required to conduct the motion for 5 times for linear pushing and fixed rotating respectively.

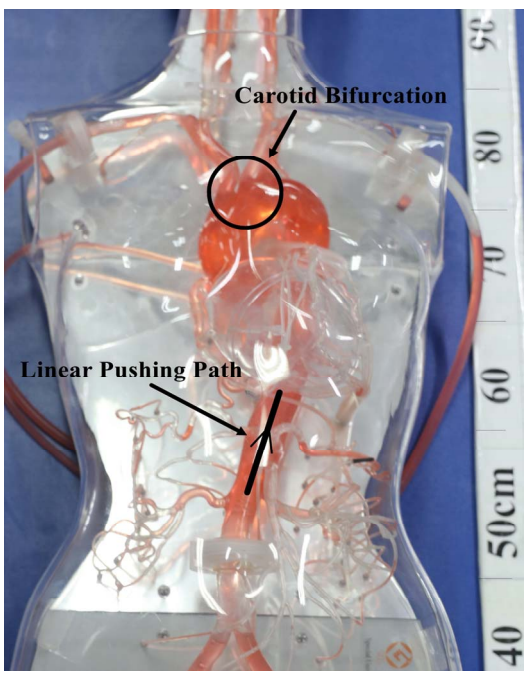

Fig. 7. Experimental Setups for Operative Paths.

The performance analysis of the algorithm are dicussed within data. To quantify the performance, we employ the root mean square (RMS) defined as

$$\text{RMS(s)} = \sqrt{\left(\sum_{k=1}^{k=m} (s_k)^2 / m\right)}, \qquad (10)$$

where m is the number of samples and s_k is the input signal at instant k. Based on RMS, %Accuracy is defined as

$$\%\text{Accuracy} = \frac{RMS(s) - RMS(e)}{RMS(s)} \times 100; \qquad (11)$$

where e is the prediction error between the actual signal and the predicted signal.

B. Setups of Evaluation Experiment

As being researched before, sEMG is claimed to be a better standard method to verify physiological tremor than regular movement signal analysis. In our research, sEMG signal is sampled together with the moving records. The set of sEMG electrode patches is that the wrist, forearm and middle finger are equipped with patches. Hence, the sEMG signal would be recorded relatively accurate in order to obtain ideal sEMG records.

C. Results of Recognition Experiment and Discussion

In this part, the result of comparison between LS-SVM and MWLSSVM is firstly shown. Later, the comparison among MWLSSVMAF and other algorithms is listed. Then, the recognition evaluation result compared to standard sEMG signal is demonstrated.

For the first comparison test, the prediction error of LS-SVM and that of MWLSSVM is demonstrated in Fig. 8, in which (a) is the actual signal, (b) is the result of MWLSSVM and (c) is the prediction error of LS-SVM. The average estimation accuracy obtained with MWLSSVM is 96.62 ± 1.24%.

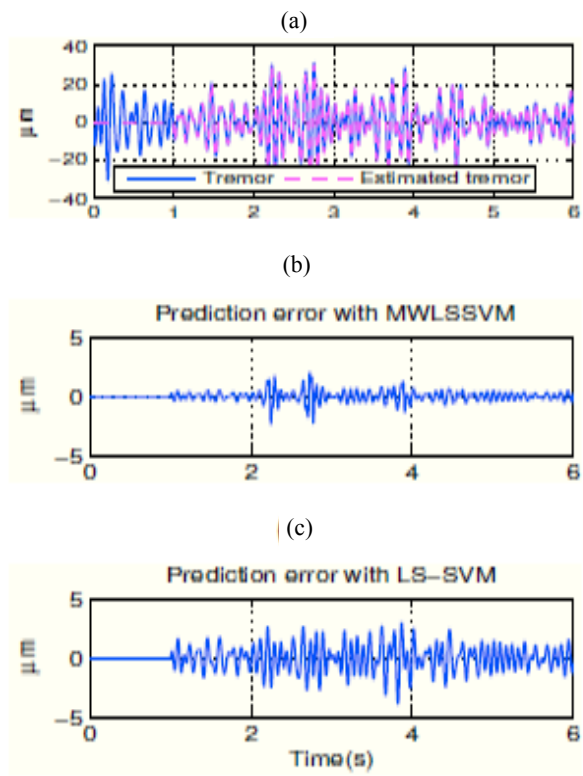

Fig. 8. Experimental Setups for Operative Paths (figure (a)represents the signal of tremor and the prediction signal, (b) demonstrates the prediction error with MWLSSVM, and the (c) shows the prediction error with LS-SVM).

Meanwhile, our research compared the proposed method with other methods from Ref. [36] in order to validate our designed approach. The estimation accuracy of MWLSSVM-AF, BMFLC-KF [36], WFLC-KF [36] and LS-SVM are

tabulated in Table 1. MWLSSVM-AF shows good estimation performance.

Table. 1 Comparison with existing methods.

S. No.	Method	% Accuracy
1	WFLC-KF	92.43±0.64
2	BMFLC-KF	99.97±0.02
3	LS-SVM	94.54±2.56
4	MWLSSVM	96.62±1.24

The third experimental result focuses on the comparison between the MWLSSVMAF and the standard sEMG signals.from the actual experiment, the consistency between the recognition result of proposed method and that of standard sEMG records is 83%, which confirms the feasible of our designed approach. The comparative figure is shown as Fig. 9.

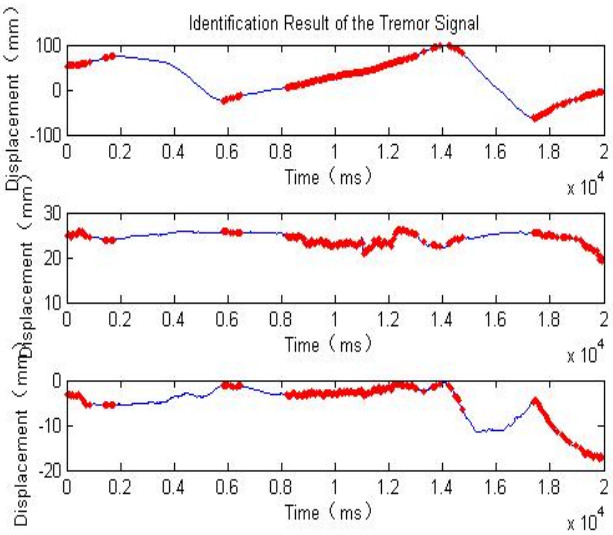

Fig. 9. Recognition results compared with sEMG records in three dimensions.

IV. Conclusion

This research proposes a LSSVM-based algorithm for physiological tremor recognition to solve the online canceling of tremor signal with such accuracy. From the aspect of computational complexity, the designed method takes less time on signal processing than common SVM algorithm. And the comparison between the MVLSSVM and LS-SVM shows that the prediction error of MWLSSVM is smaller than that of LS-SVM. Also, the accuracy indicators among proposed methods for physiological tremor cancelling are demonstrated and the result implies that the MWLSSVM performs better than other methods. Meanwhile, our research compares the recognition moving signal with the sEMG signal under the synchronous detection, whose results indicates that our algorithm possess an 83% consistency with the sEMG records. However, there are still some problems to be solved. In this research, the proposed algorithm is based on moving data machine learning and evaluated by standard records of sEMG while the True Right Rate still need to be improved and the online procedure of the tremor recognition requires to be applied in real surgeries for validation. Therefore, the application of actual practice of our approach will be conducted and the improvement will be the focuses of our future work.

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References

[1] R. Taylor, D. “Stoiariovici, Medical robotics in computer-integrated surgery,” *IEEE Trans Rob. Autom*, vol. 19, no. 5, pp. 765-781, 2003.

[2] C. Jr, “Robotic-assisted percutaneous coronary intervention filling an unmet need,” *J. Cardiovasc. Trans. Res.*, vol. 5, no. 1, pp. 62-66, 2012.

[3] C. Riga, C. Bicknell, M. Hamady, N. Cheshire, “Evaluation of robotic endovascular catheters for arch vessel cannulation,” *J. Vasc. Surg., vol.* 54, no. 3, pp. 799-809, 2011.

[4] C. Riga, C. Bicknell, A. Rolls, N. Cheshire, M. Hamady, “Robot-assisted fenestrated endovascular aneurysm repair (FEVAR) using the Magellan system,” *J. Vasc. Interv. Radiol*., vol. 24, no. 2, pp. 191-196, 2013.

[5] E. Khan, W. Frumkin, G. Ng, S. Neelagaru, F. Abi-Samra, J. Lee, M. Giudici, D. Gohn, R. Winkle, J. Sussman, B. Knight, A. Berman, H. Calkins, “First experience with a novel robotic remote catheter system: Amigo™ mapping trial,” *J. Interv. Card. Electrophysiol*., vol. 37, no. 2, pp. 121-129, 2013.

[6] M. Faddis, W. Blume, J. Finney, A. Hall, J. Rauch, J. Sell, K. Bae, M. Talcott, B. Lindsay, “Novel, magnetically guided catheter for endocardial mapping and radiofrequency catheter ablation,” *Circulation*, vol. 106, no. 23, pp. 2980-2985, 2002.

[7] Z. Feng, G. Bian, X. Xie, Z. Hou, J. Hao, “Design and evaluation of a bio-inspired robotic hand of percutaneous coronary intervention,” *in Proceeding of 2015 IEEE the International Conference of Robot and Automation*, pp. 5338-5343, 2015.

[8] C. Meng, J. Zhang, D. Liu, B. Liu, F. Zhou, “A remote-controlled vascular interventional robot: System structure and image guidance,” *Int. J. Med. Robot Comput. Assisted Surg.*, vol. 9, no. 2, pp. 230-239, 2013.

[9] J. Shen, S. LI, D. Chen, Y. Yan, “Design and experiment of guide wire tele-manipulation system based on laser mouse sensor,” *Chinese J. Med. Inst.*, vol. 36, no. 1, pp. 32-35, 2012.

[10] M. Tavallaei, D. Gelman, M. Lavdas, A. Skanes, D. Jones, J. Bax, M. Drangova, “Design, deveolopment and evaluation of a compact telerobotic catheter navigation systgem, ” *Int. J. Med. Robot Comput. Assisted Surg.*, vol. 12, no. 3, pp. 442-452, 2016.

[11] N. Zakaria, T. Komeda, C. Low, K. Mahadhir, “Development of foolproof catheter guide system based on mechatronic design,” *Prod. Eng.*, vol. 7, no. 1, pp. 81-90, 2013.

[12] N. Xiao, S. Guo, J. Guo, X. Xiao, “Development of a kind of robotic catheter manipulation system,” *in Proc. of 2008 IEEE Int. Confer. Robot Biomi.*, pp. 32-37, 2008.

[13] N. Xiao, J. Guo, S. Guo, T. Tamiya, “A robotic catheter system with real-time force feedback and monitor,” Australas Phys. Eng. Sci. Med., vol. 35, no. 3, pp. 283-289, 2012.

[14] N. Xiao, L. Shi, B. Gao, S. Guo, T. Tamiya, “Clamping force evaluation for a robotic catheter, navigation system,” *Neurosci Biomed Eng.*, vol. 1, no. 2, pp. 141-145, 2013.

[15] Jian Guo, Xiaoliang Jin, Shuxiang Guo, “Study on the Operational Safety of the Vascular Interventional Surgical Robotic System”, *Micromachines*, Vol.9, No.3, pp.1272-1288, DOI: 10.3390/mi9030119, 2018.

[16] W. Peng, N. Xiao, S. Guo and Y. Wang, "A novel force feedback interventional surgery robotic system," *in Proc. of 2015 IEEE International Conference on Mechatronics and Automation*, pp. 709-714, 2015.

[17] S. Guo, C. Xu, N. Xiao, Y. Wang and W. Peng, "A novel application of positioning method with force feedback for interventional surgery robot,"

in Proc. of 2016 IEEE International Conference on Mechatronics and Automation, pp. 437-441, 2016.

[18] S. Guo, R. Shen, N. Xiao, X. Bao, C. Xu, "A study on telecommunication technology and remote-control algorithm in minimally invasive surgical robotic system," *in Proc. of 2017 IEEE International Conference on Mechatronics and Automation*, pp. 485-490, 2017

[19] Linshuai Zhang, Shuxiang Guo, Huadong Yu, Yu Song, Takashi Tamiya, Hideyuki Hirata, Hidenori Ishihara, "Design and performance evaluation of collision protection-based safety operation for a haptic robot-assisted catheter operating system", *Biomedical Microdevices*, DOI:10.1007/s10544-018-0266-8, 2018.

[20] P. Slack, X. Ma, "Time dependency assessment of muscular fatigue index and hand tremor under operating conditions," *in Proc. of IEEE 2007 Int. Confer. Of the EMBS*, pp. 4822-4825, 2007.

[21] K. P. Bhatia, P. Bain, N. Bajaj, R. J. Elble, M. Hallett, E. D. Louis and et al., "Consensus statement on the classification of tremors, from the task force on tremor of the International Parkinson and Movement Disorder Society," *Movement Disorders*, vol. 33, no. 1, pp. 75-87, 2018.

[22] B. Taheri, D. Case, E. Richer, "Adaptive suppression of severe pathological tremor by torqueestimation method," *IEEE Transactions on Mechatronics*, vol. 20, no. 2, pp. 717-727, 2015.

[23] R. A. Maclachlan, B. C. Becker, et al., "Micron: an actively stablized handheld tool for microsurgery," *IEEE Transactions on Robotics*, vol. 28, no. 1, pp. 195-212, 2012.

[24] A. Ghorbanian, M. Zareinejad, S. M. Rezaei, H. Sheikhzadeh, K. Baghestan, "A novel control architecture for physiological tremor compensation in teleoperated systems," *Int. J. Med. Robotics Comput. Assist. Surg.*, vol. 9, pp. 280-297, DOI: 10.1002/rcs.1436, 2013.

[25] H. Sang, C. Yang, F. Liu, J. Yun, G. Jin, F. Chen, "A zero phase adaptive fuzzy Kalman filter for physiological tremor suppression in robotically assisted minimally invasive surgery," *Int. J. Med. Robotics Comput. Assist. Surg.*, vol. 12, pp. 658-669, 2016.

[26] S. Chandra, M. Hayashibe, A. Thondiyath, "Empirical mode decomposition-based filtering for fatigue induced hand tremor in laparoscopic manipulation," *Biomedical Signal Processing and Control*, vol. 31, pp. 339-349, 2017.

[27] S. Tatinati, K. C. Veluvolu, S. M. Hong, W. T. Latt, W. T. Ang, "Physiological tremor estimation with autoregressive (AR) model and Kalman filter for robotics applications," *IEEE Sensors Journal*, vol. 13, no. 12, pp. 4977-4985, DOI: 10.1109/JSEN.2013.2271737, 2013

[28] S. Guo, M. Qin, N. Xiao, Y. Wang, W. Peng and X. Bao, "High precise haptic device for the robotic catheter navigation system," *in Proc. of 2016 IEEE International Conference on Mechatronics and Automation*, pp. 2524-2529, 2016.

[29] Y. Wang, S. Guo, B. Gao, W. Peng and G. Li, "Study on motion following with feedback force disturbance in interventional surgical robot system," *in Proc. of 2016 IEEE International Conference on Mechatronics and Automation*, pp. 485-489, 2016.

[30] S. Guo, W. Peng, N. Xiao, Y. Wang, C. Xu and G. Li, "The evaluation of a novel force feedback interventional surgery robotic system," *in Proc. of 2016 IEEE International Conference on Mechatronics and Automation*, pp. 43-49, 2016.

[31] S. Guo, G. Li, B. Gao, Y. Wang. "An improved master-slave interventional surgery robotic system with force feedback," *in Proc. of 2016 IEEE International Conference on Mechatronics and Automation*, pp. 415-419, 2016.

[32] Y. Wang, S. Guo, N. Xiao, et al. "Online measuring and evaluation of guidewire inserting resistance for robotic interventional surgery systems," *Microsyst Technol*., DOI: 10.1007/s00542-018-3750-4, 2018.

[33] X. Bao, S. Guo, N. Xiao, et al. "A cooperation of catheters and guidewires-based novel remote-control vascular interventional robot," *Biomed Microdevices*, vol. 20, no. 20, 2018.

[34] X. Bao, S. Guo, N. Xiao, Y. Li, C. Yang, R. Shen, et al. "Operation evaluation in-human of a novel Remote-controlled vascular interventional robot," *Biomed. Microdevices*, vol.20, no. 34, DOI: 10.1007/s10544-018-0277-5

[35] J.A.K. Suykens, T. Van Gestel, J. De Brabanter, B. De Moor, and J. Vandewalle, "Least squares support vector machined," *Singapore, Ed. World Scientific*, 2002.

[36] K.C. Veluvolu,and W. T. Ang, "Estimation of physiological tremor from accelerometers for real-time applications," *Sensors*, vol. 11, pp. 3020-3036, 2011.