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A Novel Type of Catheter Sidewall Tactile Sensor Array for Vascular Interventional Surgery

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***Abstract* –In minimally invasive surgery, the surgeon is exposed to X-ray, threatening the surgeon's health due to depositing long. It is important to find a method instead of using X-ray during MIS. And the force feedback is the key factor for surgeon to operate this system successfully. In this paper, we developed a novel catheter sidewall tactile sensor array, which is based on a developed robotic catheter operating system with a master-slave structure. It can detect the force information between the catheter sidewall and the blood vessel in detail, and transmitting the detected force information to surgeon by using the robotic catheter system. The calibration work of single tactile sensor array element was done. We designed a LED lights array to indicate the tactile sensor array elements which sensor contacts the blood vessel wall, and we can obtain the wave profile of the contacting force from the PC. Experimental results show that the response of developed tactile sensor array is quit sensitive, and we can easily distinguish which sensor in the tactile sensor array is contacting blood vessel wall. Based on the experimental result, we know that the developed tactile sensor array is suitable for interventional vascular surgery.**

Index Terms* –Vascular interventional surgery; Catheter; Tactile sensor array; force feedback.

I. INTRODUCTION

With the development of medical technology, Minimally Invasive Surgery (MIS) has become the most effective technique for vascular diseases, and it is popular for the diagnosis and treatment of endovascular diseases [1]-[3]. Vascular Interventional Surgery (VIS) is an important part of MIS [4]-[5]. In conventional VIS, Surgeons cut an incision in the groin where a catheter is inserted, surgeons control the catheter to the target under fluoroscopic guidance [6]. During the VIS, surgeons must avoid mangling the brittle blood vessel. An experienced surgeon can achieve a precision about 2mm in the surgery. So the contact force between the blood vessel and the catheter cannot be apperceived by the surgeon [7]. Therefore, acquiring of the force information between the catheter and the blood vessel is vital to the surgeon to finish the surgery safely and successfully. In most studies, the contact force between catheter tip and blood vessel is detected, but the fraction of catheter sidewall is neglected [8].

Practices have proved that the sidewall fraction is as important as the tip contact force. In previous research works, Hongtao Gao etc. have designed a kind of tactile array with the material PVDF piezoelectric film [9], which can obtain a continuous period of tactile information on the sidewall, but the signal which the PVDF conducts is very small, and the signal processing circuits are complex. Tactile sensors using pressure sensitive rubber were developed to detect the force of the catheter sidewall in our previous study [10]. The output is precise, but the sensors couldn't distinguish which side of catheter is contacting. Yili Fu etc. developed a master-slave catheterisation system for positioning the steerable catheter [11].

In this paper, we developed a 3×3 tactile sensor array with pressure sensitive rubber. The response of the developed tactile sensor array is quit sensitive, and we can distinguish which sensor in the tactile sensor array contacts blood vessel wall by using LED lights array. We can also get the value information of the fraction from the PC screen.

II. APPLICATION BACKGROUND OF THE SENSOR ARRAY

The contact information between catheter and blood vessel is essential to a robotic catheter system. The developed tactile sensor array is based on a developed robotic catheter operating system with a master-slave structure which is shown in Fig.1. This robot system contains master side and slave side, which could perform telesurgery to protect surgeon from X-ray during VIS. The surgeon operates a catheter directly on the master side, and the control commands of the master manipulator were transmitted to the slave side. Then the slave manipulator drives the catheter to insert and rotate inside the blood vessel according to the control commands from the master side [12].

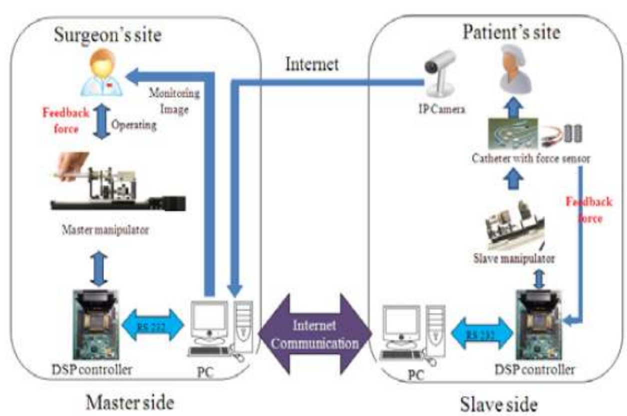

Fig.1 Conceptual diagram of the robotic catheter operating system

The key factor for surgeons to perform VIS successfully is the force feedback. The force sensor array is fixed on the front of the catheter, if the catheter contacts to the blood vessel, the force feedback could be transmitted to the surgeon's hand and eyes. Based on the force feedback, Surgeon can decide whether inserting or rotating the catheter [12]. The function of the force information in system is shown in Fig.2.

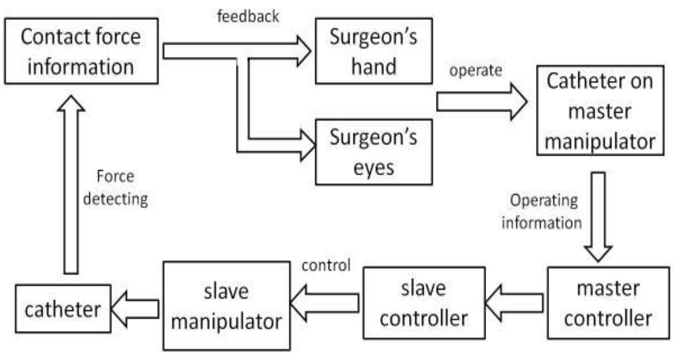

Fig.2 The function of the force information in system

III. DESIGN OF THE STRUCTURE OF THE SENSOR ARRAY

The pressure sensitive rubber is a kind of high polymer, which almost not conductive in normal situation. But the resistance rapidly decreases when loaded micro force. And when the load force reaches a certain value, the resistance will almost not be changed.

Based on the characteristic of the pressure sensitive rubber, we designed a kind of sensor array to detect the catheter sidewall contact force and fraction, 2.18mm diameter catheter for processing. The structure diagram of the sensor array is shown in Fig.3. The size of the single pressure sensitive rubber is 3×1.5×0.5mm. The copper electrode film is used to be the pole of the rubber and fix the lead wire on it. The diameter of lead wire is 0.1mm and the thickness of the copper electrode film is 0.03mm. The prototype of the developed sensor array we made is shown in Fig.4, the row distance is about 1mm, the column distance is about 0.7mm, and the hole size is 6mm×11mm. So it's fit for the catheter we use. The tactile sensor array seems to be the skin of catheter when wrapping it on the catheter sidewall. And the insulated waterproof film will be wrapped on sensor array so as to protect it from contacting with blood.

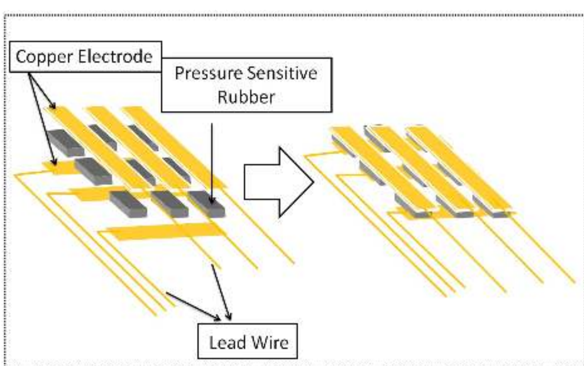

Fig.3 Structure diagram of the tactile sensor array

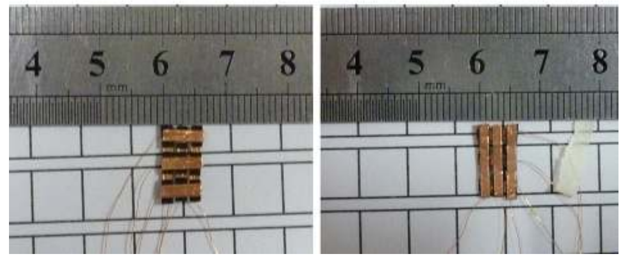

Fig.4 Prototype of the developed tactile sensor array

Multiple-path analog chips CD4051 were used to select which row and column connect to the circuit. There is only one sensor array element which located in the intersection of selected row and column works in the circuit. We got the force information of selected sensor array element through detecting the voltage of the constant value resistor. The detecting circuit is shown in Fig.5.

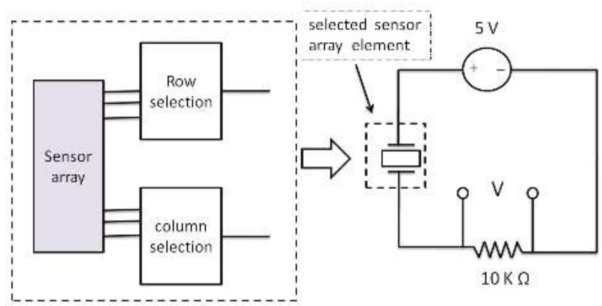

Fig.5 Diagram of detecting circuit

IV. THE ESTABLISHMENT OF SINGLE ELEMENT OF THE SENSOR ARRAY MATHEMATICAL MODEL

Research on the mathematical model of a sensor plays an important role in the production and using of sensor [9]. We calibrated the sensor array first. Due to all the sensor array elements have the same size, the calibration work should be taken only on one. The calibration system is shown in Fig.6, which consists of a data acquisition card, an electronic balance, a force load device, a serial electric circuit, a single-ship microcomputer, a DC electrical source and a PC.

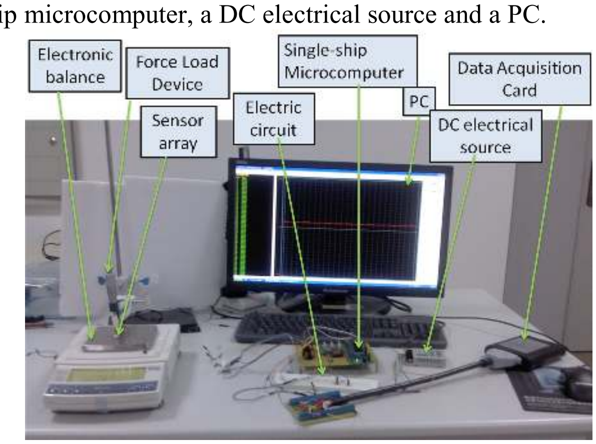

Fig.6 Calibration system for the developed tactile sensor array

We choose one of the sensor array elements to do the calibration work. The selection signal which multiple-path analog chips CD4051 used comes from the single-ship microcomputer. A constant value resistor is in series with the selected sensor array element. When the sensor array element is loaded different value from force load device, the PC will get different output voltage of the constant value resistor through data acquisition card. And we could read the value of the load force from electronic balance at the same time.

A set of data are acquired by the PC with the same load force, as is shown in the Fig.7. We used excel to get average as the voltage value for current load force. According to different load force and voltage, we got the calibration result curve with MATLAB, which is shown in Fig.8.

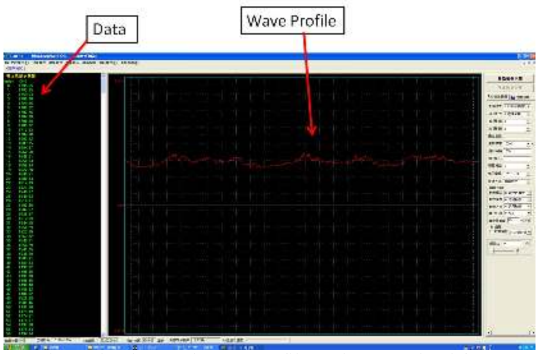

Fig.7 The data and wave profile under same load force

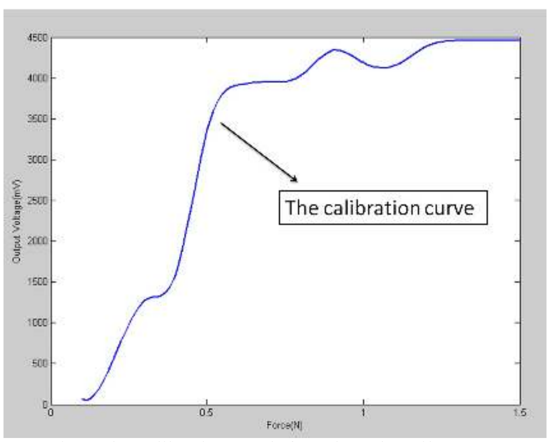

Fig.8 The calibration result for selected tactile sensor

Based on the data of correlation between the load force and the output voltage, we establish the fitting curve equation with MATLAB, it is shown in equation (1). And Fig.9 shows the Matlab curve fitting result for the sensor array single element. The fitting curve serves the display of the contacting force. The output voltage which obtained though data acquisition card could be transformed into real contacting force with the fitting curve equation.

$$f = 0.0743v^3 - 0.4168v^2 + 0.6761v + 0.0113 \quad (1)$$

Where f is the contact force, v is the voltage of constant value resistor.

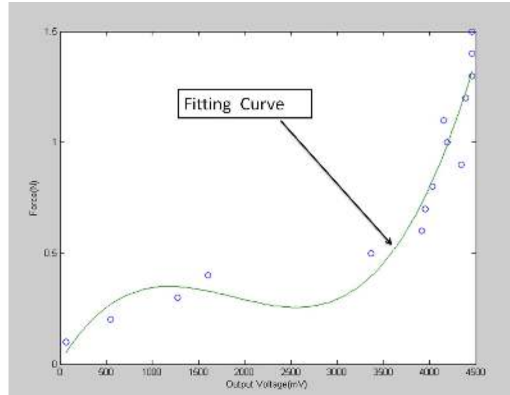

Fig.9 Matlab curve fitting result for one tactile sensor

Ⅴ. Experiment on Distinguishing Contact Information of Sensor Array

After the calibration of the sensor array, we have designed a LED lights array to indicate the sensor array elements which are contacting with the blood vessel. The lights array is shown in Fig.10. Magnitude of the contact force couldn't be gotten from LED lights. But voltage of the selected sensor array elements is acquired to show it. And the value of output voltage could be obtained from the PC screen with the type of wave. The experiment devices are shown in the Fig.11.

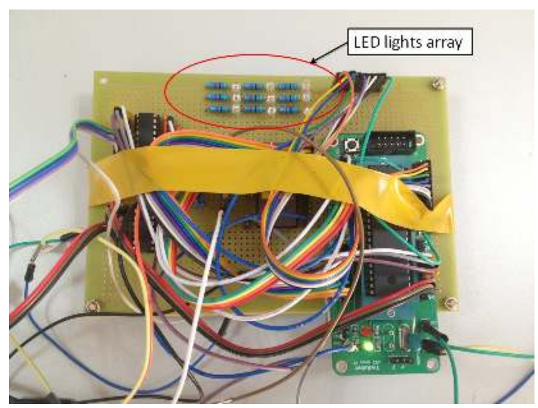

Fig.10 Diagram of LED lights array

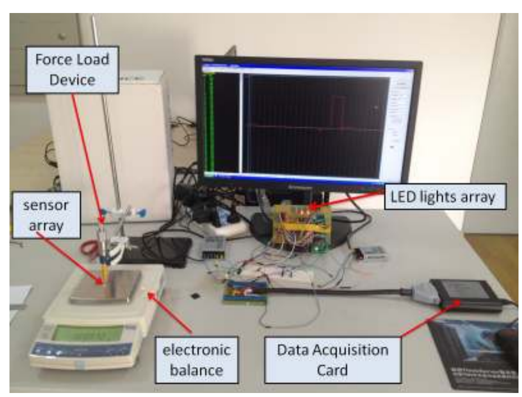

Fig.11 Experimental devices

There is one-to-one correlation between LED lights and sensor array elements. The LED lights are controlled by single-ship microcomputer. We name each of the sensor array elements with a number from 1 to 9. And the single-ship microcomputer sends selection signal to CD4051 just in this order. During each of the selected sensor array element works in the circuit, the voltage of the constant value resistor is sent out to single-ship microcomputer though analog-to-digital converter chip AD574. According to the voltage value, the microcomputer control the LED light related to the selected sensor array element lighting up or putting out. The voltage value is also acquired and sent to PC with data acquisition card.

During the operating, there may be more than one sensor array element was contacted. When some of the array elements are loaded, the related LED lights will be lighted up. As is shown in Fig.10, with the lighting LED lights 8 and 9, we could easily distinguish that the elements numbered 8 and 9 were under load force. Due to the sensor array elements are selected into the circuit in order, the voltage waves we obtain are also in order. According to lighting LED lights, we could correlate the waves with the sensor array elements one-by-one over a period of time. As Fig.12 shows, there are two waves over a period, the former one is related to sensor array element numbered 8, and the latter one is related to element numbered 9. With the voltage 172mv (equal to the load force 0.12N), the light numbered 9 is lighted up. So the sensor array is sensitive enough.

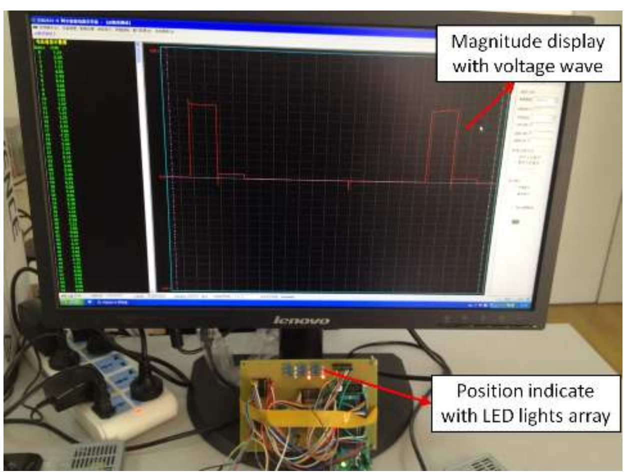

Fig.12 The display of experimental result

Ⅵ. CONCLUSION AND FUTURE WORK

A novel 3×3 tactile sensor array with pressure sensitive rubber is designed and developed in this paper. It is based on a developed robotic catheter operating system with a master-slave structure. The tactile sensor array could be installed on the catheter sidewall to detect the contacting force with the blood vessel. The signal processing circuit is easy and stable. Surgeon can decide whether inserting or rotating the catheter with the force feedback information. And the force information is the basis to operate this master-slave system. Experimental results indicate that the response of tactile sensor array is sensitive. With the help of the LED lights array and the PC screen, the operator could distinguish the position where the tactile sensor array contact with the blood vessel and obtain the force wave at the same time.

In the future work, we will improve the monitoring way of the fraction and contact force, and apply the developed tactile sensor array to the robotic catheter system for vascular interventional surgery.

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