Research on the Promotion Model and Design of 6-Degree of Freedom Force Feedback Sensor of Fault Diagnosis Manipulator

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Abstract
In this paper, the author mainly researches on the promotion model and design of 6-Degree of Freedom (DOF) force feedback sensor of fault diagnosis manipulator. Force Sensor control strategy is applied to establish haptic force feedback at end-effector of the slave manipulator. In this paper, the small changing in slave mechanics to place the sensor in the manipulator for performing different procedures such as needle injecting and ejection into the different types of experimental structures, are discussed. The controller will be designed to produce transparent haptic force feedback using force sensor and the software development according to propose strategy.
Keywords: HAPTIC FORCE FEEDBACK SYSTEM, 6 DEGREE OF FREEDOM FORCE FEEDBACK SENSOR, FAULT DIAGNOSIS MANIPULATOR

1. Introduction

The six-component force/torque sensor can measure the force and moment information together in three-dimension coordinate space. Recently, the wide-range six-component force/torque sensor becomes the urgent need high-tech product, which can be used in thrust testing of rocket engines, flight testing of airplane, testing of spacecraft docking simulation and wind tunnel. In order to overcome obstacle of traditional joints' friction to precision of wide range six-component force sensor, this paper presents the relative systematic research on the wide range parallel six-component force sensor with flexible joints.

With the development of science and technology, six-axis accelerometers are receiving more and more attention. But its research hasn't been mature yet, and being in the initial stage both at home and abroad, there are still many problems to be solved. In this paper the dynamic characteristics of a 6-SSR six-axis accelerometer are studied, static and dynamic analysis are two mainly contents as good dynamic characteristics is based on good static characteristics.

Based on the screw theory, the statics force of the Stewart six-component force sensor is analyzed in Kim's paper [1], and the static mapping matrices expression of the Stewart platform six-component force sensor is derived. The selection principle of the task-oriented six-component force sensor base coordinate system is discussed. Based on the definition of six-component force sensor's performance evaluation indices and with the theory of the space physical model, the performance indices atlases of sensor are plotted. The law of the indices following the changing of force sensor structure parameters is summarized. With the built optimization objective function, six-component force sensor is optimized design, and sensor structure design parameters with integration choiceness performance are obtained. Based on influence coefficient method and principle of virtual work, continuous stiffness nonlinear mapping general model of spatial parallel mechanism is presented in Xin's paper [2]. Combining Rayleigh quotient of the continuous stiffness matrix, the performance index k used to estimate the special parallel mechanism continuous stiffness is defined. The stiffness performance of the six-component force sensor with flexible joints is analyzed, and the directional stiffness characteristic is discussed. Based on the adjoin representation on lie group and lie algebra SE(3)/se(3), the linear-bilinear formulation of six degree-of-freedom parallel mechanisms is deduced, and the dynamic functional expressions of six degree-of-freedom parallel mechanisms are developed. The flexible joints are introduced into the wide-range six-component force sensor structure design. The structure of sensor parts are designed, and the materials are selected. Force and mode of the whole sensor structure scheme are analyzed. The prototype model of the wide-range six-component force sensor with flexible joints is designed and developed in Lan's paper [3]. The machine structure and the hydraulic power unit of wide range six-component force sensor calibration device are designed, and the big tonnage six-component force loading device with hydraulic system is developed. The signal acquisition and processing hardware system of six-component force sensor is built, and the calibration and measure software is developed in Cai's paper [4]. The calibration system of wide range six-component force sensor with flexible joints is developed. It lays a solid foundation for static and dynamic calibration experiment research of wide range six-component force sensor with flexible joints, and has important guidance significance for development of sizable six-component force sensor.

2. Force Sensor Based Force Feedback System

The new architecture is introduced in this paper for producing haptic force feedback element based on 6-DOF force sensor at master handheld device. Force sensor is placed on the slave manipulator behind the surgical tool (biopsy needle). Force Sensor control strategy is applied to establish haptic force feedback at end-effector of the slave manipulator. In this paper, the small changing in slave mechanics to place the sensor in the manipulator for performing different procedures such as needle injecting and ejection into the different types of experimental structures, are discussed. The controller will be designed to produce transparent haptic force feedback using force sensor and the software development according to propose strategy.

The Force Sensor (FS) based master slave system is presented in figure 1. The Force information is sent to controller to achieve transparent haptic force feedback on master handheld haptic device during slave interaction with environmental constraint. The M3813A six axis force/torque sensor is used to develop haptic force feedback system. The block diagram and the implementation of the force sensor in the slave side of the suggested FS haptic system are shown in figure 1.

Whenever biopsy needle interacts with environmental constraint such as injection or ejecting into the piecewise model, the contact force signals are produced [5-6]. This contact force transfers to the force sensor and the force sensor converts into some voltage levels and the voltage levels are transmitted to the controller for further processing.

Controller transforms this information into force feedback scale according to haptic device and force feedback effects can be sensed on handheld master haptic device. The Force Sensor based controller depends on the real force from the force sensor. The refresh rate of the controller should be high as much as possible in terms of slave force sensor [7]. In proposed force sensor based surgical system, the force sensor is placed between slave end-effector and surgical tool. When surgical tool (surgical needle or blade) interacts with the sample, the force is transferred to the sensor and the sensor generate some voltage level proportional to the applied force from the surgical environment. These voltage levels are transmitted to the controller and controller transforms or converts this voltage level to meaningful information for the master haptic device. The master haptic device responds according the force applied to the sensor .The force sensing based controller diagram is shown in figure 2.

As mentioned earlier, the proportional controller is designed to control slave end-effector to track the master haptic device (HD). The proposed tele-robotic control system with force sensor based haptic force feedback system is presented in Figure 2. The force inputs (FsUrg) are given by the surgeon/operator to the master omage.6 HD. The Master HD changes its position and the position sensors inside the HD update the original position of the hand according to applied force from the operator. Master positions (PM_{in}) are the inputs of the controller. Scaling factor (Ks) is used to increase or decrease workspace of the slave side (default value of Ks is 1.00), therefore Ks is multiplied with PM_{in} of the HD. The PMK_{in} is the input of difference [8]. The difference is calculated between the reference point (PMK_{in}) and the slave actuator position PS_{out} (measured by the slave position sensors). The difference is multiplied by the proportional coefficient of the controller (Kp). Slave actuator input (SA_{in}) is simply the difference of mas-

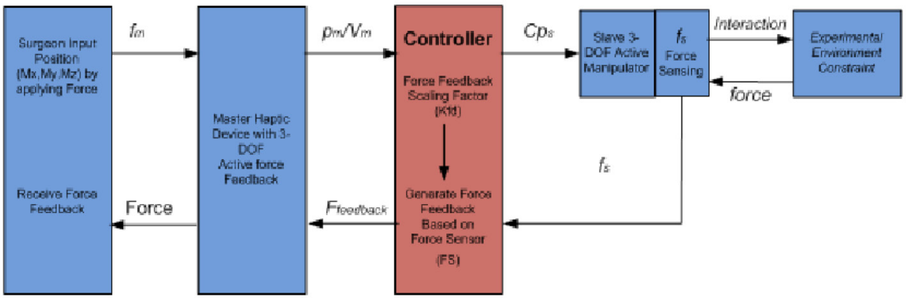

Figure 1. The Basic Model for 6-DOF Control

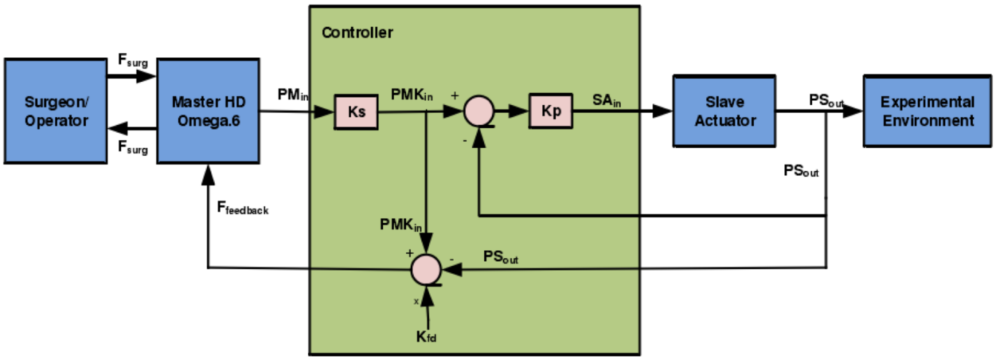

Figure 2. The Process for 6-DOF Sensor Controller

ter and slave positions with proportional coefficient of controller (Kp). This difference is multiplied with Kp to obtain the new position of slave actuator PS_{out}. The refreshing frequency of the system is high to get real time movement without time delay. On the other hand, the force sensor is placed with the slave side to make force feedback whenever environmental constraint occurs. The refreshing rate of the force sensor must be same as master haptic loop. Finally stiffness coefficient (Kfa) factor is included to increase or decrease the stiffness according the surgical procedure on the haptic device.

As mentioned above, the proportional controller is designed to control slave end-effector to track the master haptic device (HD). The force inputs (FsUrg) are given by the surgeon/operator to the master omage.6 HD. The Master HD Changes its position and the position sensors inside the HD update the original position of the hand according to applied force from the operator. Master positions (PM_{in}) are the inputs of the controller. Scaling factor (KS) is used to increase or decrease workspace of the slave side (default value of Ks is 1.00), therefore KS is multiplied with PM_{in} of the HD. The PMK_{in} is the input of difference. The difference is calculated between the reference point (PMK_{in}) and the slave actuator position PSo-t (measured by the slave position sensors). The difference is multiplied by the proportional coefficient of the controller (Kp). Slave actuator input (SA_{in}) is simply the difference of master and slave positions with proportional coefficient of controller (Kp). This difference is multiplied with Kp to obtain the new position of slave actuator PSo-t.

3. The Algorithm Based Software Design

After designing the control strategy to force sensor based force feedback system, the most problematic task in this technique is to employ force sensor in the real world. There are two applications which have to be integrated for information exchange. The force sensor application is also designed in Visual C++ 2008 language for maintaining the uniformity and improve data exchange rate between master slave and force sensor application.

Visual C++ 2008 is used in software designing. Visual C++ provides Graphical user interface (GUI) environment for developing application. Sunrise Auto Safety Technology Co,. and LTD (SRI) provides application programming Interface (API) to program, calibrate interface with computer. The force sensor supports CAN Bus or RS232 communication with different baud rate. The default Baud rate of RS232 is 11522bps and this rate can be changed by using UARTCFG command. In addition, Microsoft Foundation Class (MFC) from Microsoft Corporation and Robotic and Haptic Software development Kit (SDK) from Force and Dimension Corporation are used to design and implement the application software. Application software should be equipped with monitoring and graphical facility; hence the user can visualize the motion and feels the force feedback effect on the screen and hand respectively. Software enhances the transparency and visual and haptic force feedback from the slave side. The operator or surgeon becomes more confident and comfortable during surgical procedure. The procedure of the additional program designing is summarized as follows.

1) In the main haptic force feedback program the "RUN SENSOR" control button is available. By clicking this button, a new force sensor program is opened as shown in figure 2. The name of this application is M812_5-Demo.

2) There are different types of control available such as button, editor, combo boxes and etc.

3) "Open Port" control button is used to start the communication with RS232 port. Before pressing, set the Port Name and Baud rate by using combo-box.

4) If no error message on the "Rich Edit Window" then Config System button is pressed. Config system button is programmed to calibrate and decouple sensor according to required condition.

5) Finally "Start Real Time" control button is pressed to get continued force the data from the sensor.

The algorithm can be expressed as following equation (1-2):

$$X = 2\pi k + \pi - \alpha_1 - \pi M \sin Y \quad (1)$$

$$u_{P1}(X,Y) = \begin{cases} 0 & X \begin{cases} < 2\pi k + \pi - \alpha_1 - \pi M \sin Y \\ \geq 2\pi k + \pi - \alpha_1 + \pi M \sin Y \end{cases} \\ E/6 & X \begin{cases} < 2\pi k + \pi - \alpha_1 + \pi M \sin Y \\ \geq 2\pi k + \pi - \alpha_1 - \pi M \sin Y \end{cases} \end{cases} \quad (2)$$

The double Fourier series of function $u_{P1}(X,Y)$ is given:

$$u_{P1}(X,Y) = \frac{A_{00}}{2} + \sum_{n=1}^{\infty}(A_{on} \cos nX + B_{on} \sin nY) + \sum_{n=1}^{\infty}(A_{mo} \cos mX + B_{mo} \sin mY) \quad (3)$$
$$\sum_{m=1}^{\infty}\sum_{\pm 1}^{\pm\infty}[A_{mn} \cos(mX+nY) + B_{mn} \sin(mX+nY)]$$

In the above formula

$$A_{mn} + jB_{mn} = \frac{2}{(2\pi)^2} \int_{-\pi}^{\pi}\int_{-\pi}^{\pi} u_{P1}(X,Y) e^{j(mX+nY)} dXdY \quad (4)$$

Take the formula (2) into formula (4), then we get:

$$A_{mn} + jB_{mn} = \frac{E}{6\pi^2} \int_0^{\pi}\int_{2\pi k+\pi-\alpha_1-\pi M \sin Y}^{2\pi k+\pi-\alpha_1+\pi M \sin Y} e^{j(mX+nY)} dXdY$$
$$= \frac{E}{j6m\pi} e^{jm(n-\alpha_1)} [\frac{1}{\pi}\int_0^{\pi} e^{jmM\pi \sin Y} e^{jnY} dY - \frac{1}{\pi}\int_0^{\pi} e^{-jmM\pi \sin Y} e^{jnY} dY] \quad (5)$$

By Bessel function,

$$\frac{1}{\pi}\int_0^{\pi} e^{jmM\pi \sin Y} e^{jnY} dY = J_n(mM\pi)\frac{e^{jn\pi}-1}{2} \quad (6)$$

$$\frac{1}{\pi}\int_0^{\pi} e^{-jmM\pi \sin Y} e^{jnY} dY = J_n(mM\pi)\frac{1-e^{jn\pi}}{2} \quad (7)$$

Then,

$$A_{mn} + jB_{mn} = \frac{E}{j6mn} e^{jm(\pi-\alpha_1)} [J_n(mM\pi)\frac{e^{jn\pi}-1}{2} - J_n(mM\pi)\frac{1-e^{jn\pi}}{2}]$$
$$= j\frac{E}{6mn} J_n(mM\pi) e^{jm(\pi-\alpha_1)} [1-e^{jn\pi}] \quad (8)$$

When n=0 or n is the even number, $1-e^{jn\pi}=0$, $A_{mn} + jB_{mn} = 0$.

When n is odd number, $1-e^{jn\pi}=2$.

$$A_{mn} + jB_{mn} = j\frac{E}{3m\pi} J_n(mM\pi) [\cos m(\pi-\alpha_1) + j\sin m(\pi-\alpha_1)] \quad (9)$$

$$A_{mn} = -\frac{E}{3m\pi} J_n(mM\pi) \sin m(\pi-\alpha_1) \quad (10)$$

$$B_{mn} = \frac{E}{3m\pi} J_n(mM\pi) \cos m(\pi-\alpha_1) \quad (11)$$

When m=0, $e^{jm(\pi-\alpha_1)}=1$

$$A_{0n} + jB_{0n} = \frac{1}{2\pi^2}\int_{-\pi}^{\pi}\int_{-\pi}^{\pi} u_{P1}(X,Y) e^{jnY} dXdY \quad (12)$$

As shown in figure 3, the application software is mostly same as in master slave control software. The additional feature is force sensing based force feedback presentation on the developed software and haptic force feedback on master HD in real time. The Force sensing data acquisition software is also designed and integrated with the main software for real time force data exchange.

4. The Experiment Analysis

Before starting the experiment on different structure, the first experiment is conducted in free air to calculate the offset error of the force sensor in the

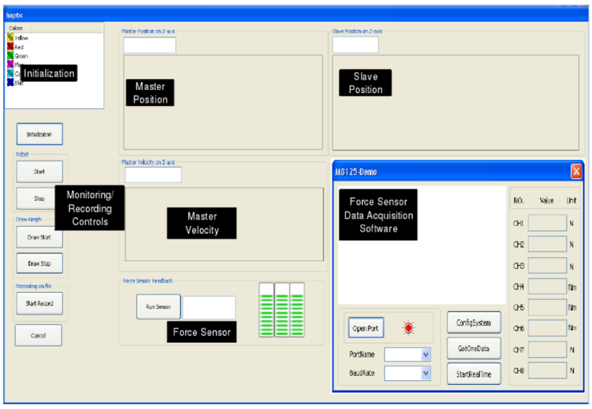

Figure 3. The Software Interface

manipulator. The experimental results are shown in figure 4. The first graph is about master random positioning in millimeter (mm) with all axes. Different color shows different axis movement in all three graphs, haptic X Y and Z axes movements belong to Blue Red and Green respectively. The maximum error from the force sensor in free space movement is about less than 10.20N on each axis as shown figure 4 .These errors occur due to random jerks during change of the direction of the master device

Experimental result on pig Tissue: The experimental results are shown in figure 5. The upward and downward Z-axis movement is shown in green. The biopsy needle injecting and ejecting experiment is performed four times on the tissue. During injecting different places of pig tissue, we have got maximum injecting force than or ejecting on about -6.0 N ejecting is about 2.5 N. In this experiment the insertion forces are shown in negative region and extraction force on positive. According to the force amplitude the force feedback element is calculated and transferred to the master handheld manipulator. This force amplitude multiplied by the stiffness factor is transferred to master device. The master device user feels the high stiffness during slave injecting and low stiffness during ejecting as shown in figure 6.

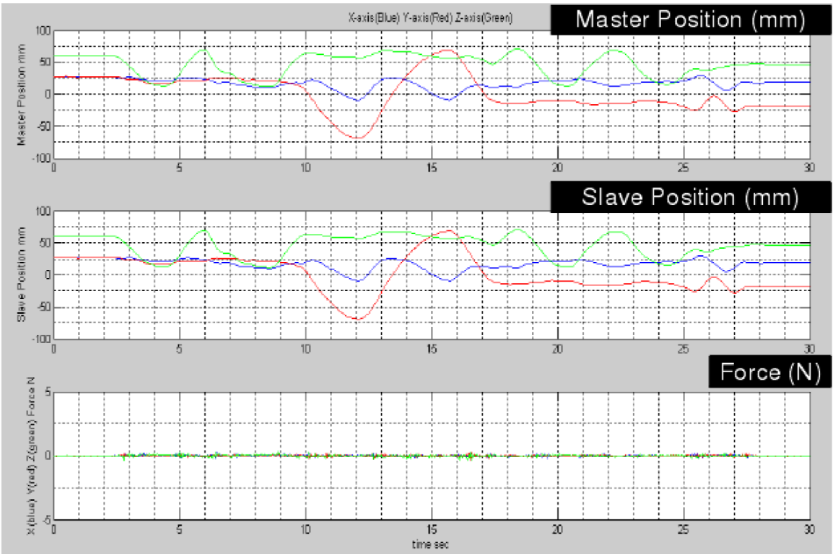

Figure 4. Experimental Results in Free Movement

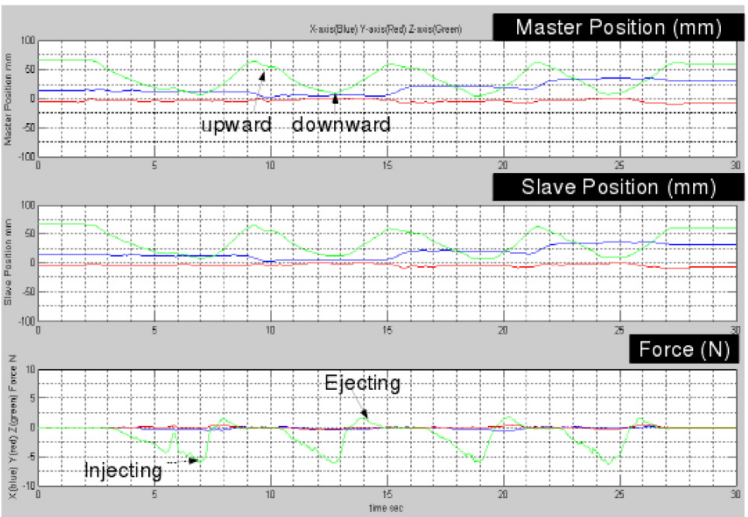

Figure 5. Experimental Results in Pig Tissue

Conclusions

In this paper, the author mainly researches on the promotion model and design of 6-Degree of Freedom (DOF) force feedback sensor of fault diagnosis manipulator. Force Sensor control strategy is applied to establish haptic force feedback at end-effector of the slave manipulator. The machine structure and the hydraulic power unit of wide range six-component force sensor calibration device are designed, and the big tonnage six-component force loading device with hydraulic system is developed. The signal acquisition and processing hardware system of six-component force sensor is built, and the calibration and measure software is developed. The calibration system of wide range six-component force sensor with flexible joints is developed. It lays a solid foundation for static and dynamic calibration experiment research of wide range six-component force sensor with flexible joints, and has important guidance significance for development of sizable six-component force sensor.

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