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Research on safety strategy of surgical robot based on virtual fixtures

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Abstract: *The safety strategy of the virtual fixtures surgical robot based on the impedance conductance control technology is proposed for the safety problems caused by the doctor's misoperation during the human-machine co-surgery. In this paper, the virtual fixtures technology is applied to the surgical operation process of human-machine co-surgery in combination with the conductance control method. Based on the good position accuracy control ability of the robot conductance control, the human-machine co-surgical motion of the doctor is restricted to the range allowed by the virtual fixtures planning, Finally the simulation results show that, the safety strategy of surgical robot based on virtual fixtures can reduce the error of the surgical robot and ensure the safety of the robotic surgical operation.*

Keywords: *impedance admittance control, virtual fixtures, surgical robot, human-machine collaboration*

1. Introduction

Artificial total knee arthroplasty is a new application of micro-invasive technology in orthopedics, and the number of operations is increasing every year, but it also brings many problems. For example, prolonged surgical operations can lead to tremors in the surgeon's hands, thus increasing the risk of the operation, and the accumulation of large amounts of X-ray radiation can cause some damage to the surgeon's body[1] . In order to improve the safety and precision of surgery, surgical robots have been introduced for artificial total knee total knee arthroplasty[2] . Baumeyer[3] et al. established the Leoni patient-assisted positioning system, which uses the principle of admittance control to realize the co-operation of medical personnel and 6-DOF robots to improve the accuracy of surgery.

In practice, robotic surgery still poses safety risks due to issues such as robotic accuracy [4] .Therefore, the safety of surgical robot remains a major research priority for the medical field. Virtual fixtures technology is introduced to the robot control to guarantee the safety of the whole surgery process. The concept of virtual fixtures was first introduced by Professor Rosenberg in 1993[5] Virtual fixtures have been introduced in robot-assisted surgery to provide reasonable guidance and constraints on the spatial motion of the end actuating mechanism for a robot to prevent accidental injuries. As a result, virtual fixtures are widely used in the medical field. Davies et al[6]who generated a forbidden virtual fixtures to assist robotic operation in knee surgery.

In the surgical operation phase, Due to the narrow area, it is easy for the surgeon to drag the robot outside the surgical area, which will cause damage to human tissues and bring great psychological pressure to the surgeon. Therefore, it is necessary to establish some areas around the surgical area where the robot is forbidden to reach to prevent damage to important tissues and improve the safety of the surgical operation.

Based on these above, the virtual fixtures technology is applied to the surgical operation process of human-machine collaborative surgery in combination with the robot admittance control method in this paper, and a surgical safety strategy is constructed based on the virtual fixtures in the surgical area. To improve the safety of surgical faulty operation.

2. Fundamentals of virtual fixtures based on impedance and admittance control

2.1 Principle of virtual fixtures-based conductance control

Admittance theory, derived from mechanical impedance, is an equivalent network idea based on generalized inertia, damping, and stiffness[7] , and is centered on establishing a mapping relationship between the operator input force and the robot end output motion.

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$$M_d(\ddot{x}_{ref} - \ddot{x}) + B_d(\dot{x}_{ref} - \dot{x}) + K_d(x_{ref} - x) = F_h \tag{1}$$

M_d, B_d, K_d are the generalized inertia, damping and stiffness of the robot, respectively, F_h are the forces applied by the operator of the robot end, $\boldsymbol{x}$ is the actual displacement at the end of the robot, and x_{ref} is the reference displacement of the robot end. The M_d effect of inertia in the man-robot collaborative system can be neglected, and the recovery force is not required in the dragging operation, K_d which can also be neglected[8] . Therefore, equation (1) can be simplified as:

$$B_d * V = F_h \tag{2}$$

$\boldsymbol{V}$ denotes the output speed of the robot end. Introducing the virtual fixtures rule[9] in equation (2) , the expression formula of the safety policy for the virtual fixtures-based admittance control can be obtained as follows.

$$V = C_d * G(f) * F_h \tag{3}$$

The admittance gain is the inverse of the damping and **G**(f) denotes the virtual fixtures rule.

Therefore, the safety strategy of the virtual fixtures-based admittance control can be regarded as the construction of the admittance gain rules and virtual fixtures rules. The guide gain rules can be found in the paper[10] , and the construction methods of the second type of virtual fixtures are mainly illustrated here.

2.2 Prohibited virtual fixtures based on artificial potential field

The forbidden virtual fixtures prevents the robot from entering the hazardous area by constructing a forbidden subspace. Figure 1 shows the schematic diagram of the forbidden virtual fixtures, where $\rho(P_{tool})$ is the distance of the robot from the forbidden area and the area *F* is the forbidden area.

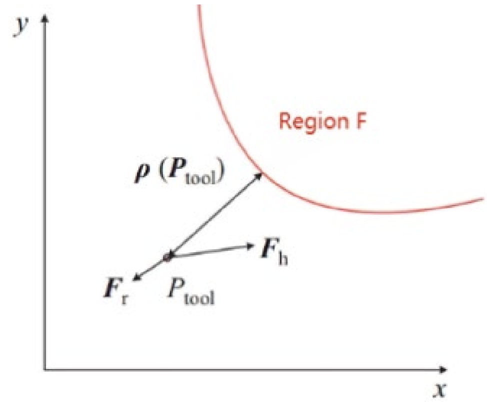

Figure 1: Prohibition type virtual fixtures

As $\rho(P_{tool})$ gets smaller, the robot should be subjected to an increasing obstructive force to prevent the robot from crossing the region *F*. This situation where the robot gets closer to the region boundary while the human-robot interaction is increasingly obstructed can be put by the mathematical model of "artificial potential field"[11].

$$F_r = \begin{cases} \eta\left(\frac{1}{\|\rho(P_{tool})\|} - \frac{1}{\rho_{max}}\right)\frac{1}{\|\rho(P_{tool})\|^2}\frac{\partial P}{\partial P_{tool}}, \\ \|\rho(P_{tool})\| \le \rho_{max} \\ \|\rho(P_{tool})\| > \rho_{max} \\ 0, \end{cases} \tag{4}$$

$\frac{\partial \boldsymbol{P}}{\partial P_{tool}}=\left[\frac{\partial \boldsymbol{P}}{\partial P_x}\frac{\partial \boldsymbol{P}}{\partial P_y}\frac{\partial \boldsymbol{P}}{\partial P_z}\right]^T$ is the difference vector of the distance between the robot and the forbidden area, η is the potential field constant, ρ_{max} is the maximum distance of the potential field, $\boldsymbol{F}_r$ is the force on the robot in the potential field. When $\|\boldsymbol{\rho}(\boldsymbol{P}_{tool})\|$ tends to 0, the force $\boldsymbol{F}_r$ tends to infinity. In order to avoid excessive forces in practice, a safety distance is set outside the forbidden area $\boldsymbol{\rho}_{min}$. When $\|\boldsymbol{\rho}(\boldsymbol{P}_{tool})\|<\rho_{min}$, $\|\boldsymbol{F}_r\|=F_{max}$, the maximum force that the robot is allowed to receive. Therefore, equation (5) is rewritten as follows.

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$$F_r=\begin{cases} F_{max} * \frac{\partial P/\partial P_{tool}}{\|\partial P/\partial P_{tool}\|}, \|\rho(P_{tool})\| < \rho_{min} \\ \eta\left(\frac{1}{\|\rho(P_{tool})\|}-\frac{1}{\rho_{max}}\right)\frac{1}{\|\rho(P_{tool})\|^2}\frac{\partial P}{\partial P_{tool}}, \\ \quad P_{min} \le \|\rho P_{tool}\| \le \rho_{max} \\ \quad 0, \qquad \|\rho(P_{too;})\| > \partial_{max} \end{cases} \tag{5}$$

The reference of the robot end is obtained.

$$V = C_d(F_r + F_h) \tag{6}$$

The F_r generated velocity component causes the robot to deviate from the prohibited area.

3. The experiments of admittance control based on virtual fixtures

3.1 The experimental procedure of virtual fixtures

In this experiment, the knee arthroplasty was performed using a forbidden virtual fixtures. By analyzing the knee joint dimensions of normal human beings and selecting the average values measured from ten people of different ages and genders, we delineated the experimental range as a circle with a radius of 30 mm. The diagram of the knee surgery range is shown in Figure 2. At the same time, in order to make the doctor softly drag the robot, the experiment was conducted based on the human input force and robot output speed data collected in the preliminary stage[12] , B_d taking 0.5 N-s/mm. Five intern volunteers were selected and each virtual fixtures was tested 10 times.

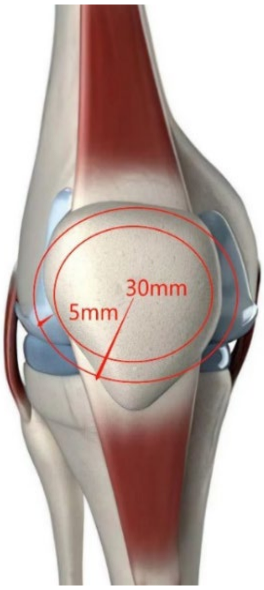

Figure 2: Schematic diagram of the scope of knee surgery

Experiment of prohibited virtual fixtures:

(1) Determination of the maximum action distance of the artificial potential field and the potential field constant η. In this experiment, the robot cannot cross the boundary of the surgical grinding area, i.e., only the forbidden area needs to be established on the inner side of the boundary. Considering the spatial size of the irregular area and the smoothness of the robot motion, the inner side of the surgical area boundary is set = 5 mm and η = 2.5 mm.

(2) Determination of the safety distance of the artificial potential field. The interior of the surgical operation area is the area where the robot needs to grind, so the position where the robot receives the maximum repulsive force in the potential field is set on the area boundary, ρ_{min} = 0 mm.

(3) Determination of the maximum force of the artificial potential field. According to the experimental study of the experimenter's input force in the previous experiment [13] , F_{max} = 1 N can make the experimenter feel the sufficient obstruction.

Researchers will use V-REP, Matlab and other software for simulation, as shown in Figure 3, and the specific virtual fixtures experimental process is as follows.

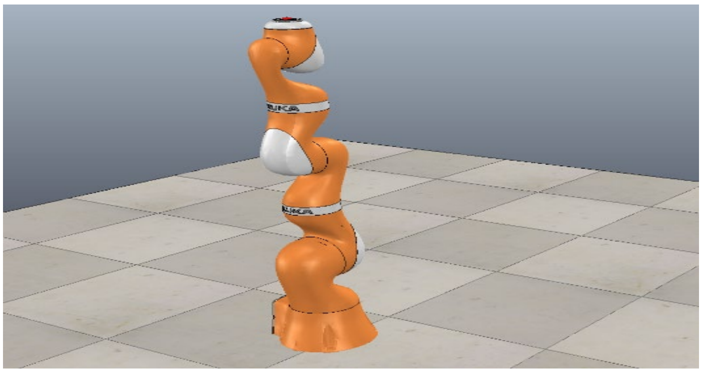

Figure 3: V-REP-kuka simulation robot model

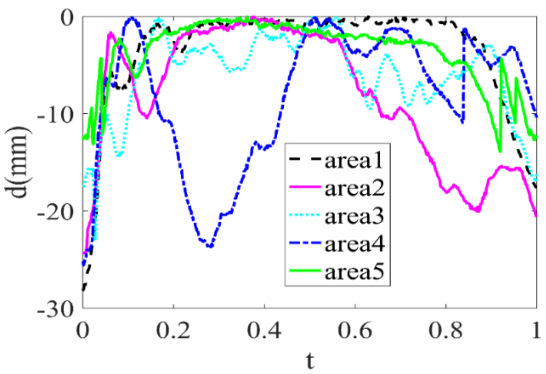

Figure 4: Distance difference diagram

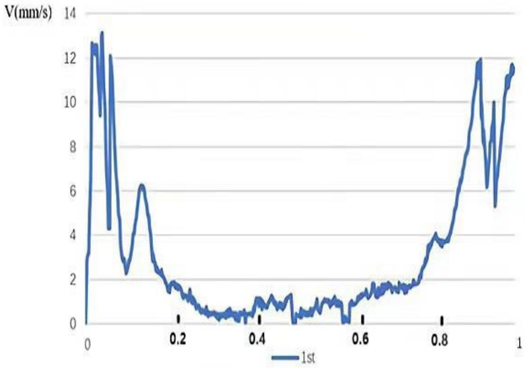

Figure 5: Rate graph

Figure 4 and Figure 5 show the simulation of the robot entering the range of action of the potential field versus the experimental time and the simulation results of the robot motion rate versus the experimental time, respectively. From the data above, it can be seen that when t=0-0.2, the motion of the robot is completely restricted to the 0-25mm region and cannot enter the 30mm region. When t=0.2-0.8, the robot is moving within the boundary and the speed is decreasing when the motion is close to the boundary, and the speed is 0 at the boundary. when t=0.8-1, the robot's motion is still limited to the 0-25mm region and the speed range is limited to 5-12mm/s. In summary, with five experiments, the motion trajectory of the robot entering the potential field grinding is completely in the 0-30mm range, while the rate starts to decrease when it approaches the boundary. In the experiments with the artificial potential field-based forbidden virtual fixtures, the virtual fixtures can restrict the experimenter's grinding operation to the grinding area, indicating that the forbidden virtual fixtures based on the artificial potential field can effectively guarantee the safety of the surgical operation.

4. Conclusion

In order to solve the safety problems caused by the doctor's faulty operation and the complexity of the surgical space in the human-robot collaborative surgery, this paper proposes a safety strategy based on the virtual fixtures for the admittance control, and constructs virtual fixtures based on the artificial potential field to avoid the doctor's injury to the important tissues during the surgery. Finally, the simulation using Matlab and V-REP software proves that the prohibited virtual fixtures can effectively prevent the robot from crossing the surgical area and achieve the protection of human vital tissues.

The current experiments studied in this paper verified the effectiveness of the virtual fixtures in the two-dimensional plane, and will be added to the three-dimensional space in the future to meet the practicality in the clinical setting.

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