Research on the Impedance Control of Human-robot Cooperative Manipulator Based on Human-friendly Technology

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Abstract. The paper had studied the human-robot cooperation with moving an object based on a three DOF (Degree of Freedom) manipulator. Firstly, the impedance control based on impedance model for the manipulator had been designed, and confirmed through the Simulink simulation. And then, the impedance parameters of the manipulator were obtained by using the least square method. For the human-friendly, the paper had proposed a new method. That is to compare the impedance characteristics of the manipulator with the impedance model of the human-human cooperation. The paper analyzed the human-friendly in quantitative by calculating the percentage error of the impedance parameters. Finally, the paper verified the human-friendly of the manipulator using the method. And it found that the designed impedance control can make the manipulator be human-friendly

Introduction

Robots have been widely used in various fields of industrial production. But most of them have been programmed and just do something simple and repeatable. With the development of robotics, robots are expected to be work in agriculture, domestic service and medicine. Usually, it is difficult for the robots to complete the task alone. Human-robot cooperation that combines the advantages of human and robot, will be more and more important.

In the papers [1-3], human-robot cooperation has been studied. They present the methods to analysis the human-friendly. Ikeura [1] let the human give marks about the feelings for viscosity, stability and maneuverability, and the feelings for the operation of the cooperation task was evaluated subjectively. Ben-Lamine [2] thought that to reach a friendly human perception during cooperation with robots, the robot has to develop the same mechanical trajectories that would be developed by some selected mass-damper-spring systems which could receive the same human force applied over the actual robot. Those selected mechanical impedances are considered friendly if they can provide a simultaneous human perception of touching something reassuring, flexible, pleasant and human-alike. All of them analysis the human-friendly by recording the feeling of the human. That is too subjectively. So they cannot analysis it in quantitative and objective. Silva [3], however, analysis the human-friendly in quantitative. He thought that the friendly perception effectiveness can be proved from the error between the speed of the friendly emulated mechanical impedance and the speed of actual vehicle when both receives the same human force. There we can see that, only the speed had been compared. It is not comprehensive in the impedance control when the force is ignored.

This paper has proposed a method to analysis the human-friendly during the human-robot cooperation. Which is to compare the impedance characteristics of the manipulator with the impedance model of the human-human cooperation. The percentage error of the impedance parameters shows the human-friendly more objective and more imprehensive.

Equations on Manipulators

The paper established the coordinate system on the manipulator through the D-H method [4],

which is show in Fig.1. The manipulator has three rotating joints, and the joint axes of each articulation are perpendicular to the paper. So the manipulator is a planar motion mechanism. Joint angle $\theta_1, \theta_2, \theta_3$ seen in Fig.1. Links length l_1, l_2, l_3 , where $l_1 = l_2$. And the mass of link are m_1, m_2, m_3 .



Fig.1. Coordinate system for manipulator with Three Degrees of Freedom We will introduce some equations for the manipulator.

(1)Forward kinematics equation

$$p_x = l_1 c_1 + l_2 c_{12} + l_3 c_{123}$$

$$p_z = l_z + l_z c_z + l_z c_{123}$$
(1)

$$p_{y} = l_1 s_1 + l_2 s_{12} + l_3 s_{123}$$

Where c_i stands for $\cos \theta_i$, s_i stands for $\sin \theta_i$, c_{ij} is $\cos(\theta_i + \theta_j)$ and s_{ij} is $\sin(\theta_i + \theta_j)$ and P_x , P_y are the positons of the endpoint of the manipulator in x axis and in y axis.

(2)Inverse kinematics equations

Since the paper mainly study human-robot cooperation moving objects along a straight line in the x axis, so $p_y = 0$. The movements of the manipulator can be seen in Fig.2.



Fig.2 movements of the manipulator

This paper studied (a). That is $0 < \theta_1 < \frac{\pi}{2}$. Using the geometric method, the result can be seen below:

$$\theta_{1} = \arccos \frac{p_{x} - l_{3}}{2l_{1}}$$

$$\theta_{2} = -2\theta_{1}$$

$$\theta_{3} = \theta_{1}$$
(2)
(3)Dynamic equation:

The dynamics of a robot manipulator describes how the robot moves in response to these actuator forces [5]. The dynamic equation of manipulator is shown as below:

(3)

$$J^{T}F + \tau = M(\Theta)\Theta + V(\Theta,\Theta) + G(\Theta)$$

Where $\Theta = [\theta_1, \theta_2, \theta_3]', M(\Theta)$ is Inertia Matrix, $V(\Theta, \dot{\Theta})$ stands for Centrifugal force and Coriolis force, $G(\Theta)$ stands for gravity, *J* stands for jacobian matrix and *F* is the outer force at the endpoint of the manipulator.

Impedance Control for the Manipulator

The force sensors attached on the endpoint of the manipulator, detected the force and the output

is taken to the computer through an amplifier and an A/D board. Then the force will be used to control the position of the endpoint of the manipulator. So it is important to convert the force applied by the human to the controller of the manipulator. [6] Two humans can finish handling an object easily. So we investigate the experiment of human-human cooperation handling an object. In the task of moving an object, we suppose that only one human knows a desired trajectory of the object and the other human does not know it. We call the former by the leader and the latter by the follower. The paper [1], which studied the human-human cooperation, had given the results below:(1) the human characteristics can be approximated by an impedance model, $f = m\ddot{x} + c\dot{x} + kx$, in which *m* is mass coefficient , *c* is damping coefficient, *k* is spring coefficient;(2) The force acted by the leader, which is defined by f_i , is nearly equal to the force acted by the follower, which is defined by f_j ;(3) they had the impedance parameter value: m = 0.5, c = 15, and the *k* is due to the follower and is almost during -3 and 15. The paper gave 5 to the *k*.

In the human-robot cooperation, the manipulator will replace the follower. So the paper studied that when people gives a force f, we convert it to the control information of the manipulator according to the equation $f = 0.5\ddot{x}+15\dot{x}+5x$. Then we control the manipulator by simple position control. And finally we can finish the human-robot cooperation task. The impedance control is implemented as shown in Fig.3.



Fig.3 Impedance control implementation

The equation $f = 0.5\ddot{x} + 15\dot{x} + 5x$ is rewritten to a vector form

$$\begin{bmatrix} \dot{x} \\ \ddot{x} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -10 & -30 \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \end{bmatrix} + \begin{bmatrix} 0 \\ 2 \end{bmatrix} f$$
(4)

The desired position of the robot in the direction of x axis is calculated in real time by the impedance model with 2 order runge-kutta method. Then we can know the desired joint angle by the inverse kinematics equations. Finally we can control the manipulator through the position control.

Simulink simulation

Simulation diagram

Each joint of the manipulator is driven by DC servo motor, and the armature controlled DC motor can be represented by the closed loop block diagram [7]:



Fig.4 armature controlled DC motor block diagram

Where R_m is armature resistance, L_m is armature inductance, I_m is armature current, V_m is armature voltage. T_m stands for motor torque and k_m stands for constant that depends on the chosen motor. Then J_z is total moment of inertia and B stands for the total viscous friction coefficient. Ω_m, Θ_m are the velocity and the angle of the motor, K_e is voltage constant.

We use PI controller to control the joint of the manipulator. And there must be a limiter module according to the rated voltage of the motor. Positon controller of the manipulator can be seen in Fig.5.



Fig.5 positon controller of the manipulator

For the whole human-robot cooperation system, we can get the desired position of the endpoint of the manipulator, which is defined by x_d , through the impedance model, that is the equation(4), with the force *f* applied by the human. Then we can get the joint angle through the inverse kinematics equations, namely the equation (2). Space conversion block diagram seen in Fig.6.



Fig.6 Space conversion block diagram

When we have the actual joint $angle \theta$, we can get the actual positon of the endpoint of the manipulator through the forward kinematics equation, namely the equation (1). The block diagram seen in Fig.7.



Fig.7 system simulation block diagram

· Results

The manipulator has $m_1 = 3kg$, $m_2 = 2.5kg$, $m_3 = 2kg$, $l_1 = l_2 = 0.3m$, $l_3 = 0.13m$. The initial position of the endpoint of the manipulator is (0.6,0) And the motor is U9M4T DC motor.

Based on the force signal measured by the human-robot cooperation with moving an object in the study [1], we can give the force information of human seen in Fig.8.



Fig.8 the force information of human

From Fig. 1 (a), (b) and (c), we can get position, velocity, and acceleration for the endpoint of the manipulator



(a) Position of the endpoint

(b) velocity of the endpoint (c) Fig.9 the experimental results

(c) acceleration of the endpoint

We got the impedance parameters of the manipulator by using the least squares method. Then the errors between the impedance parameters and the impedance model that obtained from the human-human cooperation had been analyzed. The more smaller of the error, the more human-friendly of the manipulator.

The impedance model $f = m\ddot{x} + c\dot{x} + kx$, which is rewritten to $f = u^T\beta$, where $u = [\ddot{x}, \dot{x}, x]^T$, $\beta = [m, c, k]$. We got the time sequence vector $f = [f_1 \ f_2 \ \cdots \ f_n]$, and $u = [u_1 \ u_2 \ \cdots \ u_n]$, where *n* is the sampled number.

We defined a time sequence matrix $U = \begin{bmatrix} u_1 & u_2 & \cdots & u_n \end{bmatrix}^T$, then we can find $f = U\beta + e$. To determine the parameters minimizing the *e*, then we define

$$E = \left\| e \right\|^2 = \left(f - U\beta \right)^T \left(f - U\beta \right)$$
(5)

Derivative for E

$$\frac{dE}{d\beta} = -2U^{T}(f - U\beta) \tag{6}$$

Then, if the inverse matrix of $U^{T}U$ exists, and minimizing the *e*, the parameter β is given by $\beta = (U^{T}U)^{-1}U^{T}f$ (7)

From the above process, we can get the impedance characteristic parameters of the manipulator. They are: $m_1 = 0.4914, c_1 = 14.5092, k_1 = 5.0217$.

Then, we calculate the error percentage of impedance parameters, while comparing impedance characteristics of manipulator with the impedance model obtained from human-human cooperation. Error percentage for impedance parameters is given as:

$$\frac{\Delta m}{m} = \frac{m - m_1}{m} = 1.72\%$$

$$\frac{\Delta c}{c} = \frac{c - c_1}{c} = 3.272\%$$

$$\frac{\Delta k}{k} = \frac{k - k_1}{k} = -0.434\%$$
(8)

From the above analysis, the error of the parameters is relatively small. That is the impedance characteristics of the manipulator is approximate to the impedance model obtained by the experiment that human for cooperation with the human. So we believe that the robot can be human-friendly for the human-robot cooperation with the designed impedance control.

Conclusion

In this paper, the human-robot cooperation with moving an object has been researched. The impedance control based on the impedance model had been designed to control the manipulator. Then the impedance control was simulation by using Simulink. According to the method proposed by this paper, we found that the impedance characteristics of the manipulator is approximate to the impedance model obtained by the experiment that human cooperation with human. Then, the paper believes that the robot can be human-friendly for the human-robot cooperation with the designed

impedance control.

References

[1] Ikeura R, Monden H, Inooka H. Cooperative motion control of a robot and a human [J]. Robot and Human Communication, 1994. RO-MAN '94 Nagoya, Proceedings. 3rd IEEE International Wo, 1994:112 - 117.

[2] M.S. Ben-Lamine, S.Shibata, K.Tanaka, A. Shimizu. Mechanical Impedance Characteristics of Robots for Coexistence with Humans. Proceedings of 1997 IEEE International Conference on Robotics and Automation, pp.907-912. Albuquerque, New Mexico, 1997

[3] Silva L A, de Jesus Cardoso B, Pacheco Pujatti F. Human-robot cooperation system with mechanical impedance emulation for friendly human perception[C]. Connected Vehicles and Expo (ICCVE), 2013 International Conference on. IEEE, 2013: 935-936.

[4] Craig, J J. Introduction to Robotics Mechanics & Control [M]. Chine machine press, 2006.

[5] Ding Xuegong. Research on Robot Control [M]. Zhejiang University press, 2006.

[6] Chang Huan. The Modeling and Simulation of the human-robot Cooperation Moving System [J].Machine Tool & Hydraulics, 2010, 38 (7): 117-119.

[7] Cai Zixing. Fundamentals of Robotics [M]. Chine machine press, 2009.