Fuzzy variable impedance control based on stiffness identification for human-robot cooperation

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Abstract. This paper presents a dynamic fuzzy variable impedance control algorithm for human-robot cooperation. In order to estimate the intention of human for co-manipulation, a fuzzy inference system is set up to adjust the impedance parameter. Aiming at regulating the output fuzzy universe based on the human arm’s stiffness, an online stiffness identification method is developed. A drag interaction task is conducted on a 5-DOF robot with variable impedance control. Experimental results demonstrate that the proposed algorithm is superior.

1 Introduction

Since robots have some characteristics that humans do not possess, many tasks can benefit from the physical cooperation between the two sides, such as carrying heavy objects, robot assisted assembly, robot assisted surgery, and operation teaching, etc. Robots are supposed to be provided with cooperative performance. In order to improve the flexibility of operation, active compliance is necessary when the desired position is guided by human's traction. Impedance control is a widely used technique to implement robot compliant interaction by means of establishing the mapping relationship between interaction force signal and robot motion [1].

\[ F_h = M_c \ddot{x} + B_d \dot{x} \]  

where \( F_h \) is the interaction force in Cartesian frame from human, \( M_c \) is a virtual inertia parameter, \( B_d \) is a virtual damping parameter, and \( \ddot{x}, \dot{x} \) are acceleration and velocity of robot in Cartesian space respectively. Because the restoring force is not needed in the interaction process, the virtual stiffness parameter is not considered. Among the parameters of the impedance model, the damping parameter has the greatest influence on interaction effect. Parameters for low damping can improve the ability of the robot to follow the interaction force of the operator, so that the operator could make the robot follow the flexible movement by a small force. However, a lower damping parameter limits the positioning accuracy of the collaborative interaction, and the robot would overshoot the target position. The method of constant parameter impedance control is unable to meet the need of each stage in interaction process. The key of variable parameter impedance control is how to develop a reasonable method to adjust the damping parameter. Many methods have been used to adjust the impedance control parameters. Some techniques use the stiffness of environment to regulate the impedance parameter [2,3,4,5]. These methods pay more attention to the improvement of the stability and are lack of the interaction intention estimation. To implement human-robot physical cooperation effectively and estimate operator’s intention, a fuzzy variable impedance control based on stiffness identification algorithm is proposed in this paper. The paper is organized as follows: Section 2
presents the algorithm of fuzzy adjustment for impedance parameter based on the human arm stiffness identification. An experiment is carried out in Section 3. Finally, concluding remarks are given in Section 4.

2 **Fuzzy variable impedance control based on stiffness identification**

It is difficult to define a general model to describe the trajectory of the arm’s motion, since the trajectory of the human arm is produced by the intention of human action.

![Figure 1: Estimation of interactive intention](image)

Hogan and Flash established a kinematics model of the human arm moving between two fixed points by experiment. In the case of zero starting and stopping velocity, the velocity of human arm in Cartesian frame is a bell shaped curve [6]. However, the model is only applicable to the known starting and stopping points, which is not applicable for uncertain trajectories in the interaction process. As shown in Figure 1, the operator's intention can be estimated according to the state information of the robot's velocity and the interaction force in real time. When the force and velocity are in the same direction, the intention is determined as acceleration, otherwise the intention is determined as deceleration. The bigger the force is, the stronger the intention is.

2.1 **Fuzzy variable impedance control**

Fuzzy inference system (FIS) is an effective tool for the model without accurate mathematical model. This paper presents a fuzzy variable parameter impedance control method. Based on the analysis of the interaction between human and robot, the velocity and the interaction force are used as the input variables of the fuzzy controller. Damping parameter is defined as output variable.

| $B_d$ | $F_h$ |
|-------|-------|
| NB    | NB    |
| NS    | NS    |
| Z     | Z     |
| PS    | PS    |
| PB    | PB    |

Table 1: Set of fuzzy inference rule set
The language values of the velocity variable and the interaction force variable are defined as: \{NB, NS, Z, PS, PB\}. The language values of $B_d$ are defined as: \{S, SM, M, BM, B\}. The fuzzy universe of velocity, interaction force and damping parameters are: (-2,2), (-2,2), and (1,5) respectively. Five triangular membership functions are used to represent the input and output variables. Barycentre method is applied to remove fuzziness of output. The corresponding fuzzy rules is customized according to the intention estimation strategy in Figure 1. The rule-base of fuzzy inference system is built as shown in Table 1. The control surface of $B_d$ is shown in Figure 2.

The range of output fuzzy universe is (1,5). Actual damping parameter adjustable range is set as $[A,B]$, while the output range of FIS is set as $[a,b]$. The mapping relationship between the output variable range and the actual damping adjustable range is established as:

$$ y = \frac{x-a+b}{b-a} \frac{B+A}{2} $$

where $x \in [a,b]$ is the output of FIS, $y \in [A,B]$ is actual damping parameter. In the interaction process between human and robot, the stiffness of human arm is the main factor. The effect of the inertia parameter is neglected [7]. The impedance control of the fixed parameters would lead to the instability of the system, when the stiffness of environment is high. In order to improve the cooperation ability of the robot in the interaction process, the robot must have ability to adjust its own characteristics by sensing environment.

2.2 Stiffness identification
Considering the stability and reliability of the interaction, it is necessary to adjust the parameters of impedance controller in real time. The stiffness of human’s arm has a great influence on the stability of the interaction. As show in Figure 3, where $J$ is Jacobian, in order to make the FIS adapt to the environmental characteristics, the superior limit of actual damping parameter range $B$ is adjusted according to the real-time identification of the arm stiffness. The lower bound of parameters is determined according to the interaction force and the actual speed limit of robot.
Figure 3: Block diagram of fuzzy variable impedance control based on stiffness identification

The model of operator arm stiffness identification is showed as Figure 4. It is assumed that the stiffness of operator’s arm is $K_h$ and the arm is rigidly connected to the robot end. In addition, it is assumed that the stiffness is a constant in a short time. Based on theoretic definition of stiffness, $K_h$ is represented as:

$$K_h = \frac{\Delta f}{\Delta x}$$  \hspace{1cm} (3)

where $\Delta f$ and $\Delta x$ are the change in interaction force and the change in displacement of robot end-effector respectively, which could be expressed by the following two difference equations:

$$\Delta f = F(n) - F(n-1)$$  \hspace{1cm} (4)

$$\Delta x = X(n) - X(n-1)$$  \hspace{1cm} (5)

where $F(n)$ and $F(n-1)$ are the force measured by force sensor in the adjacent sampling period. $X(n)$ and $X(n-1)$ are the sampled data of end-effector’s displacement.

In this paper, the recursive least square (RLS) method with forgetting factor is employed to identify the stiffness of operator’s arm. The general form of the recursive least squares method is expressed as:

$$y(t) = \phi^T(t-1)\theta + e(t)$$  \hspace{1cm} (6)

where:

$$\theta = (a_1, \cdots, a_n, b_1, \cdots, b_m)^T$$

$$\phi(t-1) = (y(t-1), \cdots, y(t-n_y), u(t-1), \cdots, u(t-n_u))^T$$

The following expressions are used for parameter recursive:

$$\dot{\theta}(t) = \dot{\theta}(t-1) + P(t)\phi(t-1)\left( y(t) - \phi^T(t-1)\dot{\theta}(t-1) \right)$$  \hspace{1cm} (7)

$$P^{-1}(t) = \lambda P^{-1}(t-1) + \phi(t-1)\phi^T(t-1)$$  \hspace{1cm} (8)

where $\dot{\theta}(t)$ is the parameter vector which needs to be identified, $P(t)$ is an estimation error for parameter identification, $\lambda$ is the forgetting factor. When the value of $\lambda$ is 1, it is an ordinary
recursive least square method, which is suitable for the identification of a variable changing slowly [8]. When \( \lambda \) belongs to the interval (0, 1), it is a recursive least square method with forgetting factor. For the fast changing parameters, the recursive method with the forgetting factor could reduce the influence of early data on the current identification results, so as to achieve the fast convergence. The recursive least squares method with the forgetting factor is used to identify the stiffness of human’s arm:

\[
F(n) = F(n-1) + K_h X(n) - K_x (n-1) \tag{9}
\]

where:

- \( y = F(n) \)
- \( \varphi = (F(n-1), X(n), X(n-1)) \)
- \( \theta = (1, K_h - K_x)^T \)

In order to make the results converge quickly, the forgetting factor is set as 0.99, and the recursive initial values are set as follows:

\[
\begin{align*}
\varphi_0 &= [0,0,0] \\
\theta_0 &= [1.0,0]^T \\
P_0 &= 10^{12} I
\end{align*}
\tag{10}
\]

where \( I \) is an unit matrix.

2.3 Regulation means of impedance parameter

According to the definition of impedance model in equation (1) the transfer function is expressed as:

\[
H_1(s) = \frac{1}{M_d s^2 + B_d s + K_d} \tag{11}
\]

For a typical second-order system, the transfer function is expressed as:

\[
H_2(s) = \frac{\xi}{s^2 + 2\xi \omega_n s + \omega_n^2} \tag{12}
\]

The following results is obtained when the two transfer functions are equal:

\[
\frac{1}{M_d s^2 + B_d s + K_d} = P \frac{\xi}{s^2 + 2\xi \omega_n s + \omega_n^2} \tag{13}
\]

where:

\[
\xi = \frac{B_d}{2 \sqrt{M_d K_d}}
\]

Damping ratio reflects the convergence of the system. When \( \xi \) is 1, it is the critical damping. In order to guarantee the stability and security of the interactive system, and prevent the system overshooting, damping ratio \( \xi \) should be bigger than 1. The damping parameter can be adjusted as:

\[
B_d = 2 \xi \sqrt{M_d K_d} \tag{14}
\]

3 Experimental validation

The validation of the proposed fuzzy variable impedance control scheme is conducted experimentally on a 5-DOF spine surgery robot.
Figure 5: Experimental setup with a 5 degree of freedoms spine surgery robot

The handle used for human-robot cooperation is set at the end of the robot. A force sensor (ATI-MINI45) is used to gather the force signal. The force sensor is mounted in the rear of the interactive handle. In the experiment, the human drags the robot along an unknown path in Cartesian space.

The experimental results of fuzzy variable damping parameter control without stiffness identification is shown in Figure 6. Velocity, interaction force and damping are shown in one coordinate direction, in which the damping parameter is adjusted with the change of interaction force and velocity. The data shows that the fuzzy controller could estimate the human’s interaction intention accurately. However, the lack of consideration of environmental stiffness changes leads to instability of the system which results in greater speed fluctuation. The experimental data of fuzzy variable impedance control based on stiffness identification is showed in Figure 7 and Figure 8. The adaptability to the stiffness of environment is improved, which makes the velocity more stable, the braking process faster. The interaction operation gets better performance.

Figure 6: the experimental results of fuzzy variable damping parameter control without stiffness identification

Figure 7: the experimental results of fuzzy variable damping parameter control based on stiffness identification
4 Conclusions
A fuzzy variable impedance control based on human arm’s stiffness identification was proposed in this work. To regulate the damping parameter according to the velocity and force of interaction, a fuzzy inference system is set up. A recursive least square method with forgetting factor is used to estimate the stiffness of human arm in real time. Then the stiffness is used to adjust the upper limit of damping universe. The experiment data shows that the algorithm can stabilize the process of human-robot cooperation and improve the performance.

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