Fuzzy Virtual Impedance Controller in Human-Vehicle Interaction

Shenghao Zhou  
School of Mechanical Engineering and Automation  
Northeastern University  
Shenyang, CHINA  
email:shzhzhou@mail.neu.edu.cn

Seiji Yasunobu  
Department of Intelligent Interaction Technologies  
University of Tsukuba  
Tsukuba, JAPAN  
email:yasunobu@iit.tsukuba.ac.jp

Abstract—In the previous studies mechanical impedance has become well implement in the field of human-machine interaction. However, in human-vehicle interaction there is a variant environment when driving a vehicle, thus apart from interacting with human, impedance controller is needed to adapt to the variant environment. For mechanical impedance as being a second order mass-viscosity-stiffness model with fixed parameters, it is difficult to adapt to variational constraints. In this paper, a fuzzy virtual impedance of vehicle is studied. Fuzzy virtual impedance is based on fuzzy instruction that is a fuzzy set of control instruction candidates with reasoning of Takagi-Sugeno(T-S) fuzzy model. The achieved impedance characteristics depend on the rules of T-S fuzzy model. A human-vehicle interaction experiment was preformed to demonstrate the practical application of the proposed impedance and verify the adaptability to variational constraints.

Index Terms—human-machine interaction, impedance controller, fuzzy instruction, T-S fuzzy model.

I. INTRODUCTION

Today the computer equipments have been more and more closer with human, and many studies have been done for how machines are "human friendly" so that the computer equipments may do health care for the elderly, service for human like housework, and so on [1]. To achieve a conformable human-machine interaction, it is necessary to establish a control system to interact with human [2]. Impedance controller has become well established in the field of human-machine interaction. Many methods have been developed for designing and controlling a human-machine system constructed with an impedance-controlled machine. In such studies, a human operator often take the initiative motion and machines are required to amplify/assist the human’s operation [3],[4]. In contrast, machines are required to assist the human’s operation. In such systems, the fraction of human’s operation is low during the period of the whole task, and the human’s intension is reduced.

In prior studies, systems using an impedance model can be grouped roughly into two types according to whether the machine impedance property is constant or variable [3],[5]. The mechanical impedance is mainly the second-order mass-viscosity-stiffness models with fixed parameters during operation, and although variable impedance was designed but the variable parameters could not be online adjusted [6]. In the human-vehicle system, the external environment of vehicle is changing all the time, and the support to the human’s operation need to vary according to the variant situation. Prior mechanical impedance with fixed parameters is only interrelated with one variable and it is difficult to adapt to the variant situation. In human-vehicle interaction, vehicle should provide the initiative motion to reduce the human’s workload and a variable impedance to adapt to the change of surrounding situation.

II. VIRTUAL IMPEDANCE

In this section, the virtual impedance is realized through a combination of distance sensors and hand steering angle. Fig.1 shows how impedance force derived from the control inputs (distance to constraints and angle of hand steering). This is accomplished by creating a fuzzy instruction through a predictive fuzzy control method. In this paper, the vehicle impedance is considered and human’s hand impedance will be discussed in the subsequent paper. For general vehicle impedance control, the virtual impedance is described in global coordinates $s = [s, e, \theta]^T$, where $s$ is the distance along the roadway, $e$ is the distance of the vehicle’s center of gravity from the constraints and $\theta$ is the heading angle as shown in Fig.1. Transformation between the global and body fixed coordinates $q = [x, y, \theta]^T$ is achieved with

$$\frac{\partial p}{\partial q} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$  \hspace{1cm} (1)

In general, the virtual impedance force is based on a simple proportional derivative control law [7],

$$f_{virtual} = -K \cdot p - D \cdot \dot{p}$$ \hspace{1cm} (2)

where $K$ is the proportional gain matrix, $D$ is the damping matrix. The impedance force $f_{virtual}$ is oriented in global coordinates and must be transformed to vehicle fixed coordinates to solve for the actual impedance (steering angle and differential braking)

$$f_{actual} =([-K \cdot p - D \cdot \dot{p}]^T \cdot \frac{\partial p}{\partial q})^T.$$ \hspace{1cm} (3)

In this paper, the interaction between vehicle handling and sensor location is shown without adding any artificial damping...


\[ (D = 0), \text{and we only consider the effect of vertical direction of vehicle, thus impedance force is only depend on the distance of the vehicle’s center of gravity from constraints } e \text{ shown as Eq.(4), and } \tilde{K} \text{ is a scalar parameter.} \]

\[ f_{\text{virtual}} = -\tilde{K} \cdot e. \]

\[ f_{\text{mech}} = I_m \cdot \ddot{e} + D_m \cdot \dot{e} + K_m \cdot e. \]

In this study, the velocity of vehicle is low and the human’s hand impedance is not considered, thus \( \dot{e} \) can be considered to close to zero. Furthermore, the interaction between vehicle handling and sensor location is shown without adding any artificial damping, \( D_m \) is equal to zero. Accordingly the equation of mechanical impedance force is the same as equation (4). The stiffness \( K_m \) of the mechanical impedance is an actual part and not virtual, thus the stiffness \( K_m \) is a fixed value and cannot be adjusted. However, in virtual impedance the stiffness \( \tilde{K} \) is not a fixed parameter, and it can be adjusted according to the surrounding situation. The adjustable parameter of stiffness \( \tilde{K} \) will be adjusted based on fuzzy instruction through a predictive fuzzy control method.

### III. Fuzzy Virtual Impedance Based on Fuzzy Instruction

#### A. Fuzzy Instruction

When both human and computer execute a single task, human will intervene the control, and because the traditional computer control command is only a single instruction, it is difficult to support the change of the surrounding situations flexibly. Human decides an action consciously or unconsciously by his own sense, knowledge, the experiences, etc. Generally, human maintains two or more action candidates before making decision and will select the best one with high satisfaction rating from those candidates. At this point, human can flexibly correspond to the change of the surrounding situations. If control system can also supply some control instruction candidates, the control system will make decision like human to adapt to the different situation. Fuzzy controller can implement this goal to make decision like human to adapt to the surrounding situation. In typical fuzzy controller such as sugeno-type methodology, the control instruction was obtained by the known knowledge and fuzzy inference engine. The output of controller is one signal as a control instruction to the object after the result fuzzy set is defuzzified. Yasunobu (1991) has shown that in the predictive fuzzy controller [8], [9], result fuzzy set can supply control instruction candidates according to operation candidates which are as input set of controller, and based on these control instruction candidates the control system can interact with human [10], [11].

Fuzzy instruction is fuzzy set which are composed of the membership value of the control instruction candidates \( u = c_i \). The membership value \( \mu(c_i) \) of each discrete control instruction candidate \( c_i \) represent the satisfaction rating of the control purpose. Fuzzy instruction \( \Phi_n \) in the current state is defined by the following expressions now when the total set of the control instruction is assumed to be \( U \)

\[ \Phi_n = \int_U \mu(c_i)/c_i \]

where \( \mu(c_i) \) are the membership function of control instruction candidate \( c_i \).

At the time \( t_k \), vehicle will go from current state \( q_k^T = [x_k, y_k, \theta_k] \) to next target \( q_N^T = [x_N, y_N, \theta_N] \), and according to the current situation vehicle will have a lot of operation control candidates such as turn right \( c_1 \), turn left \( c_2 \), go straight \( c_3 \), and so on. In this study, in order to make a decision, method of predictive fuzzy controller is utilized. We assumed that the run time \( t_k \) from current state \( q_k^T \) to next target \( q_N^T \) is greater than the predict time \( t \), and predict time \( t \) is decided by the human’s reaction characteristic and run state of vehicle. Dynamic characteristic of vehicle is as a simple predict model for predictive control, and the current state \( q_k^T \) of vehicle can be gotten by sensors to be as the parameters for predict model. Each of control candidates \( c_i \) is evaluated by fuzzy inference engine based on the knowledge of human’s operation. The evaluation result of satisfaction rating \( \mu(c_i) \) is as the membership value of the corresponding control candidate \( c_i \). The satisfaction rating \( \mu(c_i) \) and control candidates \( c_i \) constitute fuzzy instruction as shown in Fig.2.

#### B. Fuzzy Virtual Impedance

Impedance controller is related to the human’s operation and the surrounding situation, and the controller adds reactive torque \( \tau_c \) that shows strength of the will of the computer to human’s operation through hand wheel. In this study, impedance \( k_{IC} \) is decided by satisfaction rating error \( k_{\phi} \), the
angle error of the optimal operation instructions $\phi^*$ and the human operating steering angle $\phi$. The expression is shown as Eq.(7), and the power $\tau_r$ can be expressed as Eq.(8).

$$k_{IC} = k_0 \Delta \phi = k_0 (\phi^* - \phi)$$  \hspace{1cm} (7)\\
$$\tau_r = k_1 k_{IC} = k_1 k_0 (\phi^* - \phi)$$  \hspace{1cm} (8)\\

where $k_0$ is satisfaction rating error between present steering angle and computer command, $k_1$ is a scaling constant. $k_0$ is decided by fuzzy instruction $\Phi_n$. The controller evaluated satisfaction rating $\mu(\phi)$ of the present operator’s steering angle $\phi$ and computer command satisfaction rating $\mu(\phi^*)$ of steering angle $\phi^*$. The controller decides $k_0$ from the fellow expression by using each satisfaction rating. The appearance of the decision of $k_0$ is shown in Fig.3.

$$k_0 = \mu(\phi^*) - \mu(\phi).$$  \hspace{1cm} (9)

![Fig. 3. Decision of satisfaction rating error $k_0$](image)

The main feature of linear Takagi-Sugeno fuzzy systems is to express the local properties of each fuzzy implication (rule) by a linear function. We assume that the linear Takagi-Sugeno fuzzy system is of the following form:

$${\text{Rule } i:} \text{ IF } x_1 \text{ is } M_{i1}, \ldots, x_n \text{ is } M_{in} \text{ THEN } y = a_i x,$$

where $x^T = [x_1, x_2, \ldots, x_n]$ are the function variables; $i = 1, 2, \ldots, r$ and $r$ is the number of IF-THEN rules; and $M_{ij}$ are fuzzy sets. The linear function $y = a_i x$ is the consequence of the $i$th IF-THEN rule, where $a_i \in R^{1 \times n}$. The possibility of the $i$th rule is given by the product of all the membership functions associated with the $i$th rule:

$$h_i(x) = \prod_{j=1}^{n} M_{ij}(x_j).$$  \hspace{1cm} (10)

We assume that $h_i$ have already been normalized, that is, $h_i(x) \geq 0$ and $\sum_{i=1}^{r} h_i(x) = 1$. Then by using the center of gravity (COG) method for defuzzification, we can represent the T-S fuzzy system as

$$y = f(x) = \sum_{i=1}^{r} h_i(x) a_i x.$$  \hspace{1cm} (11)

**THEOREM 1** For any smooth nonlinear function $f(x)$: $R^n \rightarrow R^1$ defined on a compact region, satisfying $f(0) = 0$ and $f \in C^2$, both the function and its derivatives can be approximated, to any degree of accuracy, by linear T-S fuzzy systems [12].

Under the conditions of theorem 1 there exists a smooth nonlinear function $f(x)$ to satisfy the linear T-S fuzzy system. Taylor series for several variables can become

$$T(x) = \sum_{|a| \geq 0} D^a f(a) \frac{a^T}{a!} (x - a)^a$$  \hspace{1cm} (12)\\

where $D^a f(a)$ is the Hessian matrix, $x^T = [x_1, x_2, \ldots, x_n]$, $a$ is the vector of expansion point. In this study, for simple declaration this function depends on two variables, $x_1$ and $x_2$.

$$\begin{cases} \phi = \mu(\phi^*) - \mu(\phi) = f(x^*) - f(x) = f(x^*) - f(a) - f_{x_1}(a)(x_1 - a_1) - f_{x_2}(a)(x_2 - a_2) = -f_{a_1}(x^*)(x_1 - a_1) - f_{x_2}(x^*)(x_2 - a_2) \\ \end{cases}$$  \hspace{1cm} (13)\\

i) $t_1 > t$, here $t_1$ is the time from current state $q_1$ to next target $q_N$, and $t$ is the predict time. $a_1 = e$, $a_2 = 0$, $x_1 = e$, then

$$k_0 = -f_{x_2}(x^*)x_2.$$  \hspace{1cm} (14)\\

ii) $t_1 \leq t$, $a_1 = 0$, $a_2 = 0$, $x_1 = e$, then

$$k_0 = (f_{x_1}(x^*) - f_{x_2}(x^*))x_2/e.$$  \hspace{1cm} (15)

Therefore fuzzy impedance model is expressed as

$$\tau_c = k_1 k_0 \Delta \phi = \tilde{K} \cdot e$$  \hspace{1cm} (16)

where

$$\tilde{K} = g(e, \phi, \theta)$$

$$= \begin{cases} -k_1 f_{x_1}(x^*)x_2/e \cdot \Delta \phi & t_1 > t \\ -k_1(x^*) + f_{x_2}(x^*)x_2/e \Delta \phi & t_1 \leq t \\ \end{cases}$$  \hspace{1cm} (17)

Fuzzy virtual impedance model is as second order mechanical model look, but the parameter is a function $g(e, \phi, \theta)$ of distance error $e$, steering angle $\phi$ and the vehicle posture orientation $\theta$. When the environment changed, fuzzy virtual impedance can adapt it to output proper force to human operator.

**IV. EXPERIMENT**

An overview of experimental system for the human-vehicle interaction experiment was shown in Fig.4. It consists of computer driving simulation system and driving simulator with hand wheel (WingMan FORMULA GP, Logicool Corp.). The hand wheel is actuated by a motor, and the steering angle is sensed by a potentiometer. The assisting signal is sensed by a strain gage (Resistance Value 350Ω) through a reinforcing girder.

The main purpose of this experiment is to examine the validity of fuzzy virtual impedance. Fuzzy virtual impedance that is generated by a virtual elastic body with a variable parameter ($\tilde{K}$), and different from the fixed parameter $K_m$ of mechanical impedance the variable parameter $\tilde{K}$ varies
with the surrounding situation, thus the fuzzy impedance has an adaptive characteristic according to the surrounding situation.

In this experiment, two conditions were assumed that vehicle was in neutral gear (speed is 0), and the vehicle located in the center of roadway. If the width of road is 4m, then the gravity point of vehicle locates in the point that distance to constraints (wall or bound) is 2m. Run direction of vehicle was the direction of the roadway. In this experiment only angle $\phi$ of hand wheel was changed. Simultaneously front wheel and sensors of detecting state of vehicle was turned with the change of angle $\phi$. Through moving the reinforcing girder the relation of assisting signal $P$ and angle error $\Delta \phi$ was presented. The assisting signal is between -0.5V and +0.5V. The result is shown in Fig.5.

![Fig. 4. Overview of experimental system](image)

**Fig. 4. Overview of experimental system**

The experiment results demonstrate that the developed fuzzy virtual impedance is validity and can adapt to the surrounding situation.

### REFERENCES


