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Fuzzy Virtual Impedance Controller in Human-Vehicle Interaction

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***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. But 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 varible [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 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 $p = [s, e, \theta]^T$, where s is the distance along the roadway, e is the distance of the vehicle's center of gravity from the constraints and θ 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

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

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

$$f_{virtual} = -K \cdot p - D \cdot \dot{p} \tag{2}$$

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)

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

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

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($D = 0$), 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 shown as Eq.(4), and $\tilde{K}$ is a scalar parameter.

$$f_{virtual} = -\tilde{K} \cdot e. \tag{4}$$

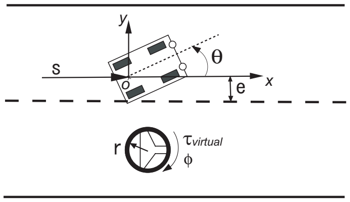

Fig. 1. Global coordinate and impedance torque

General mechanical impedance is a second-order model with distance e, inertia I_m of vehicle, viscosity D_m and stiffness K_m which is given as

$$f_{mech} = I_m \cdot \ddot{e} + D_m \cdot \dot{e} + K_m \cdot e. \tag{5}$$

In this study, the velocity of vehicle is low and the human's hand impedance is not considered, thus $\ddot{e}$ 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 Φ_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

$$\Phi_n = \int_U \mu(c_i)/c_i \tag{6}$$

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

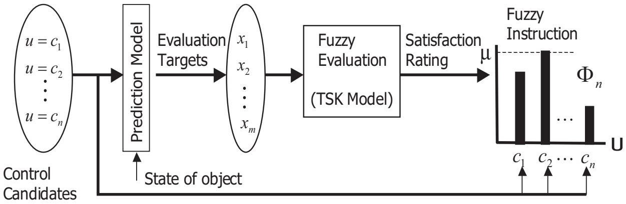

Fig. 2. Principle of fuzzy instruction

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_1 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 τ_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_ϕ, the angle error of the optimal operation instructions ϕ^* and the human operating steering angle ϕ. The expression is shown as Eq.(7), and the power τ_c can be expressed as Eq.(8).

$$k_{IC} = k_\phi \Delta\phi = k_\phi(\phi^* - \phi) \tag{7}$$

$$\tau_c = k_1\ k_{IC} = k_1\ k_\phi(\phi^* - \phi) \tag{8}$$

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

$$k_\phi = \mu(\phi^*) - \mu(\phi). \tag{9}$$

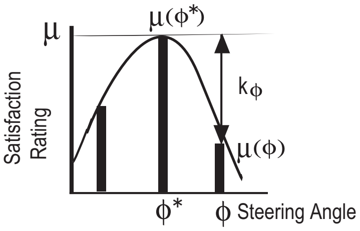

Fig. 3. Decision of satisfaction rating error k_ϕ

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:

$$\begin{aligned} Rule\ i:\ \ & IF\ x_i\ is\ M_{i1}\ \cdots\ and\ x_n\ is\ M_{in} \\ & THEN\ y = a_i x, \end{aligned}$$

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 ith IF-THEN rule, where $a_i \in R^{1\times n}$. The possibility of the ith rule is given by the product of all the membership functions associated with the ith rule:

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

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 system as

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

THEOREM 1 *For any smooth nonlinear function f(x):* $R^n \rightarrow R^1$ *defined on a compact region, satisfying* $f(0) = 0$ *and* $f \in C_n^2$*, 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

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

where $D^\alpha f(a)$ 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. x_1 represent the error e and x_2 is the vehicle orientation. And the expansion point is $a = [a_1, a_2]^T = x^*$. Hence according to the Eq.(12), the satisfaction rating error is derived as

$$\begin{aligned} k_\phi &= \mu(\phi^*) - \mu(\phi) = f(x^*) - f(x) \\ &= f(x^*) - f(a) - f_{x_1}(a)(x_1 - a_1) - f_{x_2}(a)(x_2 - a_2) \\ &= -f_{x_1}(x^*)(x_1 - a_1) - f_{x_2}(x^*)(x_2 - a_2) \end{aligned} \tag{13}$$

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

$$k_\phi = -f_{x_2}(x^*)x_2. \tag{14}$$

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

$$k_\phi = (-f_{x_1}(x^*) - f_{x_2}(x^*)x_2/e)e. \tag{15}$$

Therefore fuzzy impedance model is expressed as

$$\tau_c = k_1\ k_\phi \Delta\phi = \tilde{K} \cdot e \tag{16}$$

where

$$\begin{aligned} \tilde{K} &= g(e, \phi, \theta) \\ &= \begin{cases} -k_1 f_{x_2}(x^*)x_2/e \cdot \Delta\phi & t_1 > t \\ -k_1(f_{x_1}(x^*) + f_{x_1}(x^*)x_2/e)\Delta\phi & t_1 \leq t \end{cases} \end{aligned} \tag{17}$$

Fuzzy virtual impedance model is as a second order mechanical model look, but the parameter is a function $g(e, \phi, \theta)$ of distance error e, steering angle ϕ and the vehicle posture orientation θ. 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 (stiffness $\tilde{K}$), and different from the fixed parameter K_m of mechanical impedance the variable parameter $\tilde{K}$ varies

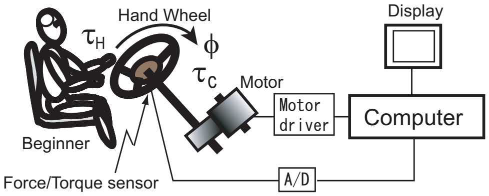

Fig. 4. Overview of experimental system

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 ϕ of hand wheel was changed. Simultaneously front wheel and sensors of detecting state of vehicle was turned with the change of angel ϕ. 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.

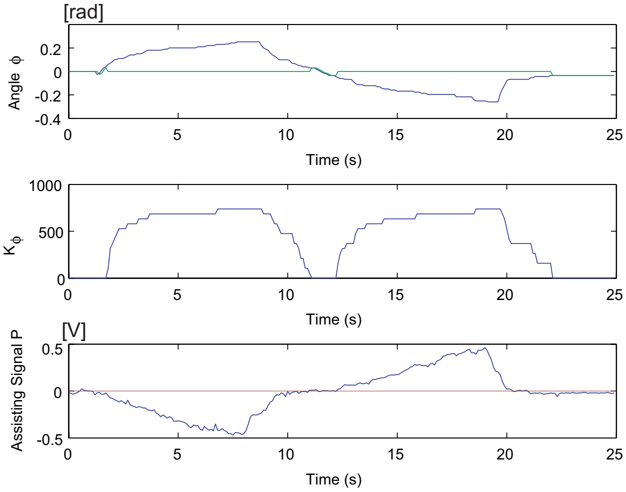

Fig. 5. Variational impedance when the distance to contraints is fixed

Fig.5 shows the varying of the k_ϕ and the assisting signal P when the angle ϕ of hand wheel is changed by moving the reinforcing girder. According to the conditions of experiment, the vehicle stands motionless, thus the distance of the vehicle's center of gravity from the constraints is a fixed value and the distance error e is zero during the whole time of experiment. According to the mechanical impedance with the fixed parameter K_m, the mechanical impedance value will be a constant and not change. However, the result based on the fuzzy virtual impedance changed with the change of hand wheel angle ϕ, furthermore, the change of fuzzy virtual impedance is nonlinear.

V. CONCLUSION

This paper proposed a new method of fuzzy virtual impedance to implement the impedance control in the human-machine interaction. Fuzzy instruction was defined as a fuzzy set of evaluation to control candidates through a predictive fuzzy control method. Then according to the simple proportional derivative control law, the strategy of fuzzy virtual impedance was developed based on fuzzy instruction. Different from the mechanical impedance with a fixed parameter stiffness K_m, fuzzy virtual impedance has a variable parameter $\tilde{K}$ according to the change of surrounding situation. The experiment results demonstrate that the developed fuzzy virtual impedance is validity and can adapt to the surrounding situation.

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