

Fuzzy Virtual Impedance Based on Fuzzy Instruction in Human-Vehicle Interaction

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Abstract—In the field of human-machine interaction mechanical impedance has become well implement. However, in human-vehicle interaction there is a variant environment when drivin a vehicle, thus apart from cooperating with human, an impedance is needed to adapt to the variant environment. But as being a second order mass-viscosity-stiffness model with fixed parameters, for mechanical impedance 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 TS fuzzy model. The characteristics of achieved impedance is as a spring part with variable parameter so as to adapt to the variant road situation. A human-vehicle cooperation experiment was preformed to demonstrate the practical application of the proposed impedance and verify the adaptability to variational constraints.

I. INTRODUCTION

Today the compute 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 cooperation, it is necessary to establish a control system to cooperate with human[2]. Impedance controller has become well extabished 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 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 on 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. STRATEGY OF FUZZY VIRTUAL IMPEDANCE

A. Virtual Impedance

In this section, the virtual impedance is realized through a combination of distance sensors and hand steering angle. Figure 1 shows how impedance torque derived form 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 Figure 1. Transformation between the global and body fixed coordinates $q = [x, y, \theta]^T$ is achieved with

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

In general, the virtual impedance is based on a simple proportional derivative control law,

$$\tau_{virtual} = (-K \cdot p - D \cdot \dot{p})r \quad (2)$$

where K is the proportional gain matrix, D is the damping matrix and r is the radius of hand wheel. The impedance torque $\tau_{virtual}$ is oriented in global coordinates and must be transformed to vehicle fixed coordinates to solve for the actual impedance (steering angle and differential braking).

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

In this paper, the interaction between vehicle handling and sensor location is shown without adding any artificial damping ($D = 0$), the impedance torque is only depend on the distance of the vehicle 's center of gravity from constraints e .

$$\tau_{virtual} = -K \cdot e \cdot r. \quad (4)$$

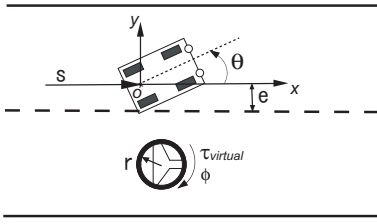


Fig. 1. Global coordinate and impedance torque

General mechanical impedance is a second-order model with distance e , inertia I of vehicle, viscosity D and stiffness K which is given as

$$\tau_{mech} = -(I \cdot \ddot{e} + D \cdot \dot{e} + K \cdot e)r. \quad (5)$$

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 is equal to zero. Accordingly the equation of mechanical impedance torque is the same as equation (4). The stiffness K of the mechanical impedance is an actual part and not virtual, thus the stiffness K is a fixed value and can not be adjusted. However, in virtual impedance the stiffness K is not a fixed parameter, and it can be adjusted according to the surrounding situation. The adjustable parameter of stiffness K will be adjusted based on fuzzy instruction through a predictive fuzzy control method.

B. 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[7], [8], 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 cooperate with human[9], [10].

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 .

$$\Phi_n = \int_U \mu(c_i)/c_i \quad (6)$$

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

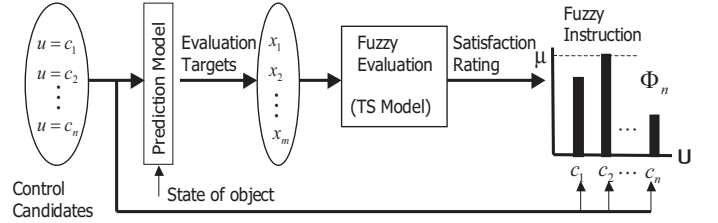


Fig. 2. Principle of fuzzy instruction

In this study, fuzzy instruction is generated by a method of predictive fuzzy control. Vehicle will go from current state to target, and operation candidates are assumed such as 'turn right($u = c_1$)', 'turn left($u = c_2$)', 'go straight($u = c_3$)', etc. The vehicle predicts the future state of each operation candidate during t second that is the expectation time to arrive the target. In this case, dynamic characteristic of vehicle is as a simple predict model for predictive fuzzy control, and the state of vehicle can be gotten by sensors to be as the parameters for predict model. Then, fuzzy inference engine based on the knowledge of human's operation is to evaluate the satisfaction rating $\mu(c_i)$ through calculating the distance to the environment constraints and target as shown in Fig.2.

C. 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_c^* 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).

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

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

Here, 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.

$$k_\phi = \mu(\phi^*) - \mu(\phi). \quad (9)$$

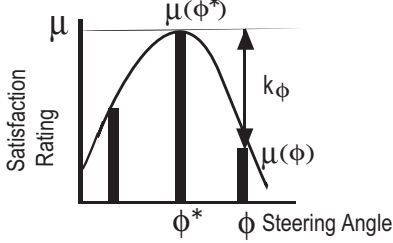


Fig. 3. Decision of satisfaction rating error k_ϕ

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:

Rule i : IF x_i is M_{i1} ... and x_n is M_{in}
THEN $y = a_i x$,

where $x^T = [x_1, x_2, \dots, x_n]$ are the function variables; $i = 1, 2, \dots, r$ 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:

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

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

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

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 [11].

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

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

where $D^\alpha f(a)$ is the Hessian matrix, $x^T = [x_1, x_2, \dots, x_n]$, 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 function of distance to target. 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

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

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. $f_{x_2}(x^*) = 0$, $a_1 = e$, then

$$k_\phi = f_{x_1}(x^*)(1 - a_1/e)e. \quad (14)$$

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

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

Therefore fuzzy impedance model is expressed as

$$\tau_c = k_1 k_\phi \Delta\phi = \tilde{K} \cdot e \cdot r \quad (16)$$

where

$$\begin{aligned} \tilde{K} &= g(e, \phi, \theta) \\ &= \begin{cases} k_1 f_{x_1}(x^*)(1 - a_1/e)\Delta\phi/r & t_1 > t \\ -k_1(f_{x_1}(x^*) + f_{x_1}(x^*)x_2/e)\Delta\phi/r & t_1 \leq t \end{cases} \end{aligned} \quad (17)$$

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.

III. EXPERIMENT

An overview of experimental system for the human-vehicle cooperation 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 350 Ω) through a reinforcing girder.

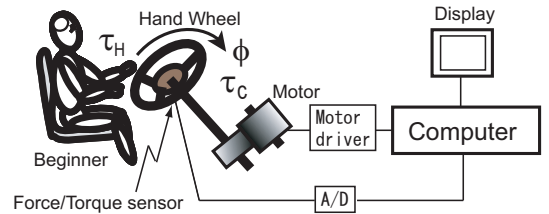


Fig. 4. Overview of experimental system

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 has a variable paramete (stiffness \tilde{K}), and different from the fixed paramete of mechanical impedance the variable paramete \tilde{K} varies with

the surrounding situation, thus the fuzzy impedance has a adaptive characteristic according to the surrounding situation.

In this experiment, two conditions were assumed that one is vehicle was in neutral gear (speed is 0), and the other is that the vehicle locates in the center of roadway. If the width of road is $8m$, then the gravity point of vehicle locates in the point that distance to constraint (wall or bound) is $4m$. Run direction of vehicle was the direction of the roadway. In this experiment only angle ϕ of hand wheel is changed. Simultaneously front wheel and sensors of detecting state of vehicle is 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 both is between $-0.5 V$ and $+0.5 V$. The result is shown in Fig.5.

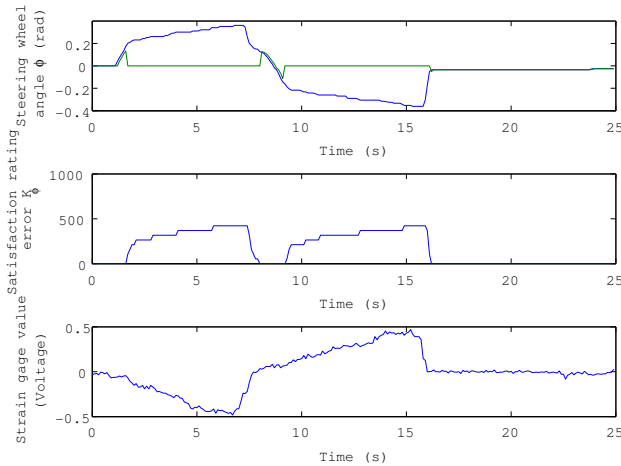


Fig. 5. Variational impedance when the distance to constraints is fixed

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 $e = 0$ during the whole time of experiment. According to the mechanical impedance with the fixed parameter K , 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.

IV. 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 with reasoning of TS fuzzy model. 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 , 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 valid and can adapt to the surrounding situation.

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