A Cooperative Auto-driving System Based on Fuzzy Instruction

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***Abstract*— This paper deals with control of auto-driving cooperative system considering the safety of vehicle. Fuzzy instruction is fuzzy set of control instruction which could be as control command candidates. According to the current situation of the vehicle the fuzzy instruction is calculated and auto-driving system is constructed. The cooperative control system was purposed to support the human's operation based on the fuzzy instruction, and the support is shown through the variable reaction force to human. An impedance controller was designed for the human's operation, and the controller which can most effectively represent the safety of the running vehicle was identified. The cooperative control system is evaluated by an experiment using driving simulator, and the validity of the proposed design procedure is confirmed.**

Keywords: Fuzzy instruction, Auto-driving system, Cooperative control system, Impedance controller

I. Introduction

In this paper, control system design of cooperative auto-driving system considering the different situations is investigated. In such a system, a human operates steering wheel in order to manipulate an auto-driving vehicle moving on the different situation. When human and computers together execute the control, it is important to establish the control system of the cooperative type with human[1]. In general, control system stably and strongly sends an optimal instruction to the object, and it is difficult to be changed by human's operation. Through fuzzy instruction we can send a set of fuzzy control commands, and human's operation can be flexibly supported.

In this study, we propose a cooperative auto-driving system based on fuzzy instruction considering the different situations. At first, the fuzzy instruction which expresses the current situation is calculated. Second, an auto-driving method is proposed. In this method, pursuit path is not necessary and tactical targets are made for path planning. And predictive control is utilized to predict the steering angle according to the current situation. Moreover, dynamic constraints are also considered. Then, a cooperative system is constructed. When human holds the steering wheel, the cooperative system does work and support the human's operation. If human releases the steering wheel, auto-driving system does work.

A. Theoretical Background

Fuzzy instruction is fuzzy set of control instructions which are composed of the membership value of the control instruction candidates. The discrete control instruction candidates represent the satisfaction rating sr_i of the control purpose. As Fig.1, control instruction candidates have 5 numbers, and we suppose that the control instruction candidates u3 is the optimal value to the control purpose, and $\mu(u3)$=1.0, the satisfaction rating sr_3 of the control purpose is 100%. Then $\mu(u2)$=0.8, and the satisfaction rating sr_2 of the control purpose is 80%. $\mu(u)$ =0.4, sr_1=40%, and so on. Fuzzy instruction Φ_n in the state is defined by the following expressions when the total set of the control instruction is assumed to be U.

$$\Phi_n = \int_U \mu_{\Phi_n}(u_i)/u_i \tag{1}$$

Here, $\mu_{\Phi_{n(u_i)}}$ are the membership values of control instruction candidate u_i, and here also as the values of the satisfaction rating sr_i.

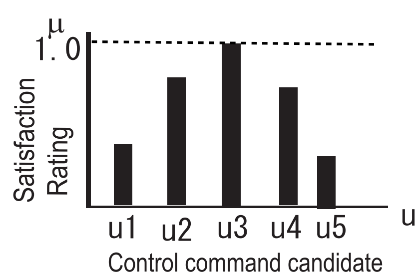

Fig. 1. Fuzzy instruction

B. Experiment Purpose

Previous study was mainly that human and vehicle cooperative control was proposed when vehicle was driven by human[2]. In this study, we investigate the cooperative method when the vehicle can automatically drive by computer control instruction. Two situations are discussed, wide road and narrow road as Fig.2. When vehicle runs on the wide road, it means that human can operate the vehicle with weak power, so the driver can change the route which the auto-driving system will run. Whereas on the narrow road, the driver will receive strong power and almost can not change the route. In this paper, the relation of the power τ_c to human and angle error $\Delta\phi$ in this two situations was explained while the vehicle was in neutral gear, and then different support to human on wide/narrow road was carried out.

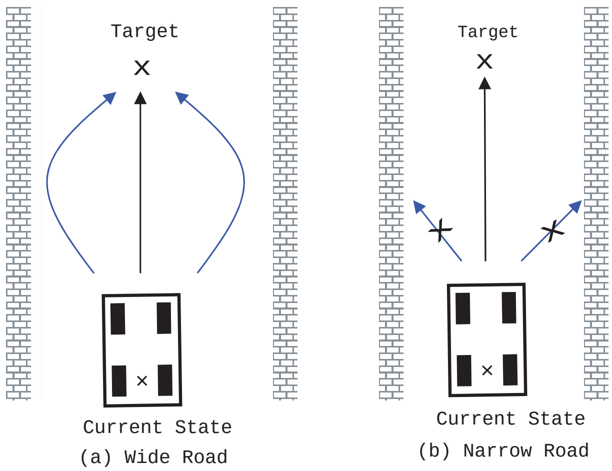

Fig. 2. The support of human's operation in different situations

II. Dynamic Characteristic of Vehicle

A simple model of the four wheel vehicle dynamics is developed. It is assumed that each wheel rolls without laterally slipping and the generation of the centrifugal force is disregarded when the velocity is very slow, thus with nonholonomic characteristics has the shown geometrical relation in Fig.3. In this case, configuration of four wheel vehicle can be described by the vector of coordinates q=$[x, y, \theta, \phi]$. The state of a present vehicle is shown by coordinates (x,y) of the middle of the rear wheel and angle θ of the x axis and the advanced direction. The front wheel steering angle ϕ is the average of of right angle ϕ_R and left angle ϕ_L, the distance of the front wheel and the rear wheel is L, the average velocity of the front wheel is υ, and the rotational velocity of the front wheel is ω. At this time, the motion equation of Ackermann-Jeantaud is

$$\frac{dx}{dt} = \upsilon\ cos(\phi)cos(\theta), \tag{2}$$
$$\frac{dy}{dt} = \upsilon\ cos(\phi)sin(\theta), \tag{3}$$
$$\frac{d\theta}{dt} = \frac{\upsilon}{L}\ sin(\phi), \tag{4}$$
$$\frac{d\phi}{dt} = \omega. \tag{5}$$

Therefore, when steering angle ϕ and velocity υ are kept constant, present position (x_0, y_0) and angle θ_0 are assumed. In that case, after t second, position (x_t, y_t) and angle θ_t calculate

$$x_t = \frac{L}{tan(\phi)}cos(kt) + x_0, \tag{6}$$
$$y_t = \frac{L}{tan(\phi)}sin(kt) + y_0, \tag{7}$$
$$\theta_t = kt + \theta_0. \tag{8}$$

Here k is

$$k = \frac{vcos(\phi)tan(\phi)}{L}. \tag{9}$$

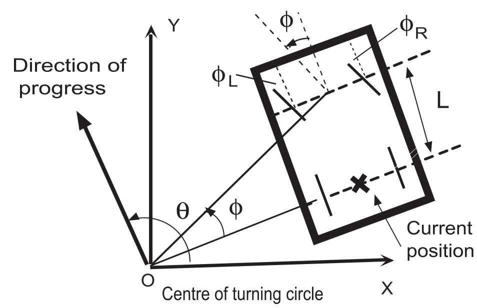

Fig. 3. Dynamic characteristic of vehicle

III. Auto-driving System

A. Control System Outline

The outline of auto-driving system using detector part, tactical setting part and predictive fuzzy control for auto-driving part is shown as Fig.4.

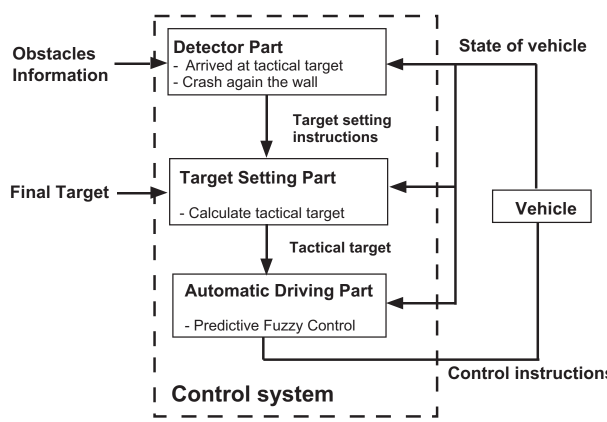

Fig. 4. Outline of Auto-driving System

B. Detector Part

The detector part detects the current state of vehicle and the distance away from the obstacles. A new tactical target for automatic driving part is needed when the current tactical target is determined to have passed.

C. Target Setting Part

The tactical target is needed in order to move the vehicle to reach the final target. And more important role is to weaken the role of the final target in order to preferably support the human's operation. In the tactical target setting part, current state of the vehicle is compared to the final target when the target setting part received instruction from the detector part. Then the tactical target is setted as the next target to be arrived.

D. Automatic Driving Part

In application to make a smooth tracking to attain the tactical target, predictive fuzzy control is utilized. The predictive fuzzy controller decides the fuzzy instruction by using the predictive fuzzy control method[3][4]. At first, operation candidates are assumed such as 'The steering wheel is turned to the right.' , 'The steering wheel is turned to the left.' etc. And the controller predicts the state of each operation candidate during t sencond. The t second 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. Secondly, fuzzy inference engine based on the knowledge of human's operation is to evaluate the satisfaction rating sr_i of the arriving to the tactical target and the distance to the environment constraints. The grade of control instruction candidates is determined by the value of satisfaction rating sr_i. The highest satisfaction rating sr_i has the highest grade. The candidate that has highest grade is assumed the optimal control instruction for the current state. Then the optimal control instruction as next computer instruction controls the direction of the vehicle to run. The process is shown in Fig.5.

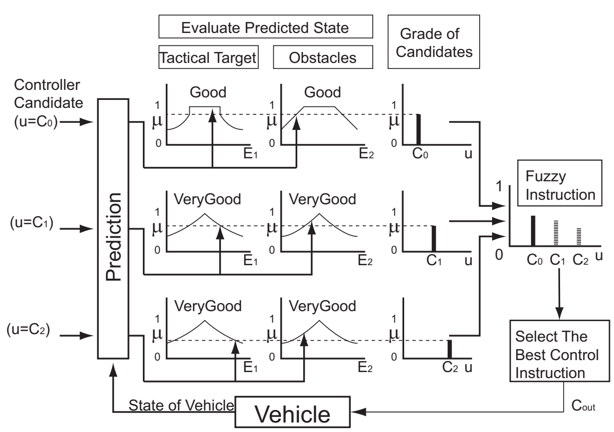

Fig. 5. Process of Auto-driving Method

IV. Cooperative Controller

The vehicle has sufficient autonomy to perform computer command actions without detailed instructions from operator, but operator can intervene the computer command actions cooperatively by steering wheel. An overview of the system is presented in Fig.6. The human tries to operate the steering wheel by power τ_h of the arm. The power τ_c is decided by cooperative control system and will change along with the increase of steering angle ϕ. The steering wheel was moved finally by necessary torque τ_T and the human will operate the vehicle in steering angle ϕ.

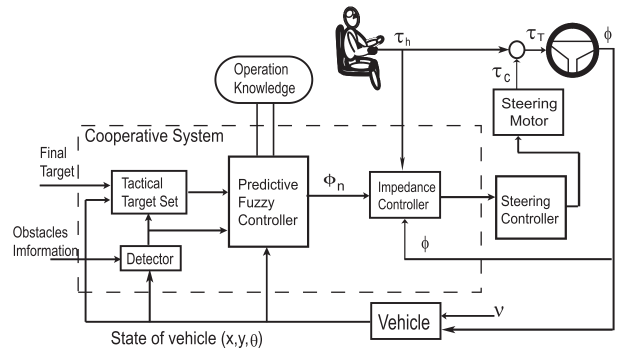

Fig. 6. Overview of cooperative auto-driving system

The controller adds power τ_c that shows strength of the will of the computer to the human's operation on there by impedance control[5]. Impedance control is nonlinear impedance control as shown in Fig.7 and on wide/narrow road the impedance is different. 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.(10). And the power τ_c can be expressed as Eq.(11).

$$k_{IC} = k_\phi \Delta\phi = k_\phi(\phi_c^* - \phi). \tag{10}$$

$$\tau_c = k_1\ k_{IC} = k_1\ k_\phi(\phi_c^* - \phi). \tag{11}$$

Here, k_ϕ is satisfaction rating error between present

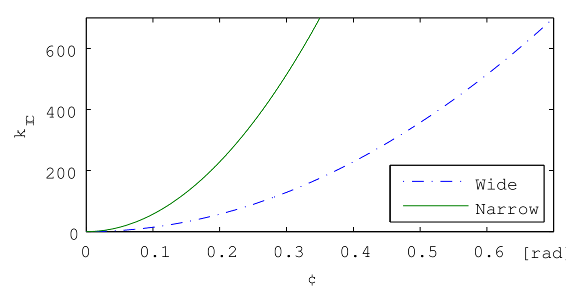

Fig. 7. Nonlinear impedance along with the increase of angle error $\Delta\phi$

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 sr_ϕ of the present operator's steering angle ϕ and computer command satisfaction rating sr_c^*. 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.8.

$$k_\phi = sr_c^* - sr_\phi. \tag{12}$$

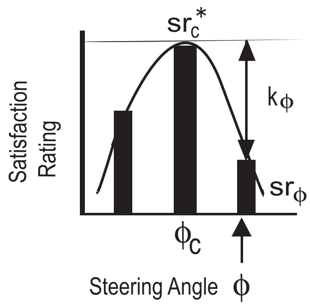

Fig. 8. Decision of satisfaction rating error k_ϕ

V. Experiment

The experimental set-up for the human-vehicle cooperation experiment was as shown in Fig.9. It consists of computer auto-driving simulation system and driving simulator with steering wheel. The steering wheel is actuated by a maximum 50 V servomotor, and the steering angle is sensed by a poentiometer. The power τ_c is sensed by a strain gage through a reinforcing girder. During cooperation control when a human moves the reinforcing girder, the increase of steering angle error is first sensed. Based on the fuzzy instructions the error of satisfaction rating is calculated. Experiment was divided into two parts. At first, the relation of τ_c and angle error $\Delta\phi$ is presented, and then the experiment of different support to human corresponding to the change of the environment is carried out.

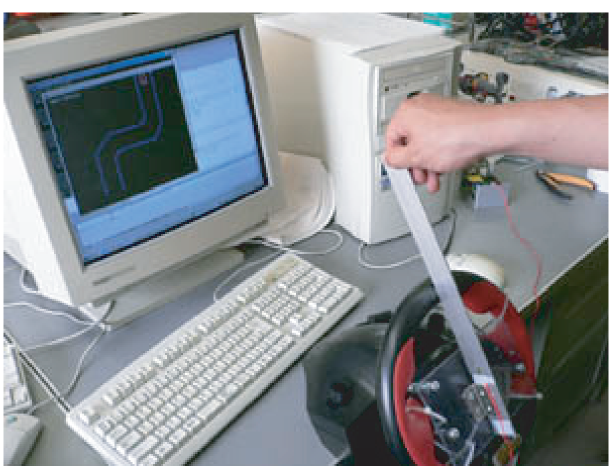

Fig. 9. Experimental setup for cooperation experiment. Photograph shows the computer auto-driving simulation system, driving simulator, the reinforcing girder, and a strain gage pasted on the reinforcing girder.

A. Relation of τ_c and $\Delta\phi$

Firstly, the experiment of the relation of τ_c and angle error $\Delta\phi$ is carried out in different road width. Wide road width is 8 m, and narrow road width is 4 m. We assumed that the vehicle was in neutral gear (velocity is 0) and the vehicle is in the centre of the road as shown in Fig.2, through moving the reinforcing girder the relation of τ_c and angle error $\Delta\phi$ was presented. On the wide road, the grade of vehicle safety is high, so the satisfaction rating error is low, and the human could move the reinforcing girder from -0.46 rad to +0.46 rad. However, on the narrow road, the grade of vehicle safety is lower, so the satisfaction rating error is higher, and human could only move the reinforcing girder from -0.25 rad to +0.25 rad. The strain gage value both is between -0.5 V and +0.5 V. The result is shown in Fig.10.

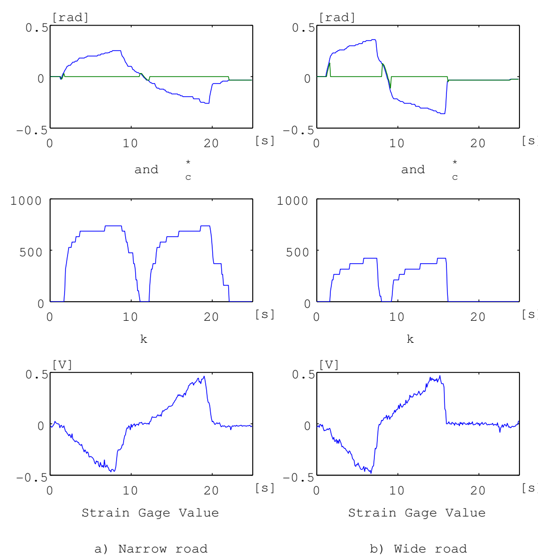

Fig. 10. Relation of τ_c and $\Delta\phi$

B. Different Support on Wide/Narrow Road

After we have known the relation of the τ_c and angle error $\Delta\phi$, the experiment of different support to human corresponding to the change of the environment is carried out based on the computer auto-driving simulation system. The computer auto-driving simulation system simulates the real-time vehicle and auto-driving system is constructed based on the fuzzy instructions. The characteristics of the vehicle is as follows. The wheelbase is 2.6 m, distance between axis and bumper is 0.4 m, width is 1.7 m, the smallest turning radius is 6 m and the velocity is 0.4 m/s. Fig.11 shows an automatic drive example on wide road (width is 8 m). The initial state is q_s=$[x, y, \theta, \phi]$=[-12.0, -10.0, $\pi/2$, 0.0], and final target is q_T=$[x_T, y_T, \theta_T, \phi_T]$=[10.0, 20.0, π/2, 0.0]. Through setting the tactical target, the vehicle moves keeping away from the obstacles from initial state to final target. In Fig.11, polylines are shown as the obstacles (e.g. wall). In order to reach the final target, three tactical targets have been setted. The tactical targets list is List = [-10.0 -2.0 π/2, 0.0; 5.0, 4.0, 0.0, 0.0; 10.0, 20.0, π/2, 0.0].

Fig.12 and Fig.13 shows the different support to human corresponding to the change of the environment. Narrow

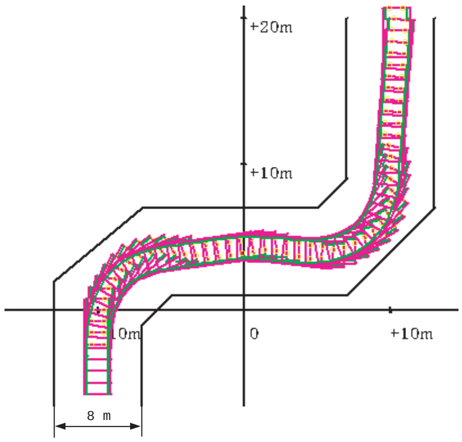

Fig. 11. An example of auto-driving trajectory on wide road (width=8m)

road width is 4 *m*, and wide road width is 8 *m*. On the narrow road, vehicle cooperated with human to move from initial point to final target, and though the strain gage value changed from minimum value to maximun value the trajectory was almost superposition with the automatic drive trajectory. On the narrow road, the support power to human was strong, and it was difficult for human to changes the route which computer command planed. However, on the wide road, vehicle cooperated with human to move from initial point to final target, the trajectory was different with the automatic drive trajectory. On the wide road, the support power to human was soft, and human could change the route observably.

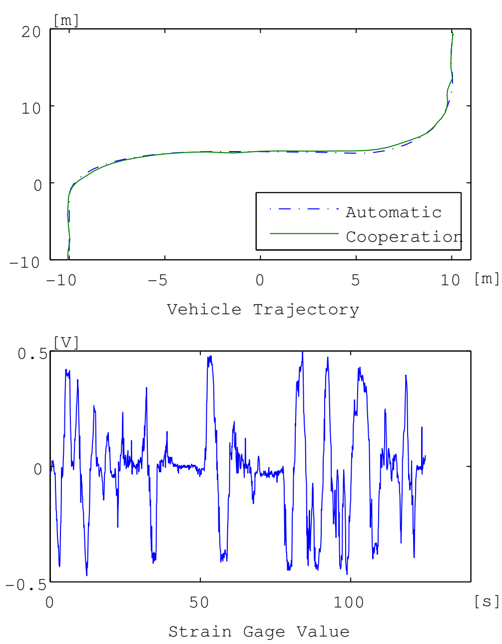

Fig. 12. The support on narrow road (width = 4*m*)

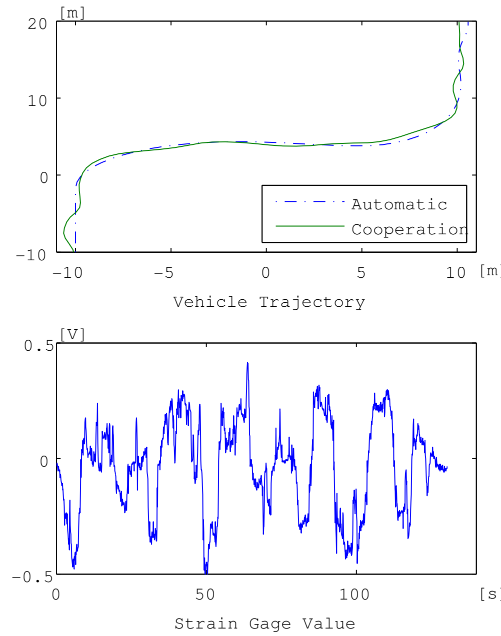

Fig. 13. The support on wide road (width = 8*m*)

VI. Conclusion

In this paper, a cooperative auto-driving method was proposed based on fuzzy instruction. In auto-driving system, tactical target was setted in order to reach the final target, and the predictive fuzzy control was utilized in the auto-driving method. The simulation of auto-driving system shows that the validity and effectiveness of the proposed method. Cooperative system was proposed to flexibly support the human's operation in different situations. As a automatic driving vehicle, when human holds the steeering wheel to intervene the motion of the vehicle, the cooperative system can response quickly and support flexibly according to the current situation, and when human releases the steeering wheel, the cooperative system will return to the state of automatic drive. Experiment with driving simulator has been done to confirm the validity of the cooperative methodology.

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