An Intelligent MIMO Control for Two-Wheeled Vehicle

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***Abstract*— Humans can control MIMO (Multiple-Input Multiple-Output) objects appropriately using knowledge of the MIMO object, which can be referred to as human MIMO control knowledge. An example of a MIMO object is a two-wheeled vehicle. A skilled operator is able to operate a two-wheeled vehicle cleverly using human knowledge. In this paper, an intelligent MIMO control (iMIMOc) method that can be built using MIMO knowledge is proposed. Furthermore, the iMIMOc method is applied to a two-wheeled vehicle, and the effectiveness is confirmed. The simulation results show the validity of this control method.**

I. INTRODUCTION

Intelligent controls are widely used, and the effectiveness of this control method has been confirmed. Zadeh proposed fuzzy set theory and fuzzy logic as a method for quantifying human qualitative evaluation indices [1]. Mamdani applied fuzzy control, which is an intelligent control, experimentally to a steam engine for the first time [2]. Yasunobu applied the predictive fuzzy control to an automatic train operation (ATO) system [3][4].

Most conventional intelligent control systems have the knowledge of a single control input. A number of MIMO (Multiple-Input Multiple-Output) controlled objects exist in the real world. Although it is difficult to control a MIMO object, humans can control such objects appropriately by using their knowledge of the MIMO object (human MIMO control knowledge).

One example of a MIMO object is a two-wheeled vehicle and there are skilled operators with a knowledge of operating a two-wheeled vehicle. In addition, a skilled operator understands the running characteristic of the two-wheeled vehicle and operates the vehicle while predicting, for example, that 'if the vehicle is leaned to the right at the present speed, it should be able to turn the corner'. In this way, a skilled operator can operate the two-wheeled vehicle skillfully by applying MIMO knowledge.

In this paper, an intelligent MIMO control (iMIMOc) method that can be built using human MIMO control knowledge is proposed. Furthermore, the iMIMOc is applied to a two-wheeled vehicle, and the validity of this control method is verified.

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II. MIMO CONTROLLED OBJECT

A. Two-wheeled Vehicle

In this paper, a two-wheeled vehicle, which is a typical MIMO object, is considered. The quality of vehicle operation is strongly influenced by the operator. Therefore, a two-wheeled vehicle is a human-machine object, as shown in Figure 1. This two-wheeled vehicle is assumed to be a motorcycle.

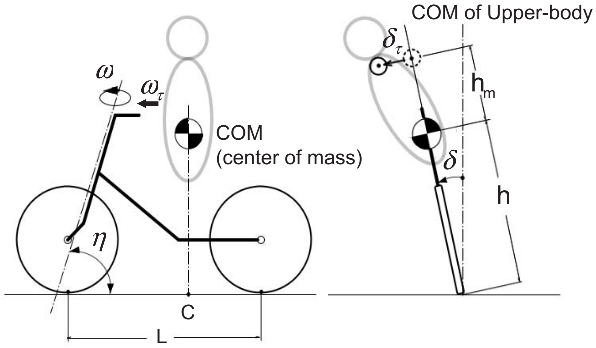

Fig. 1. The two-wheeled vehicle as a human - machine object

The motion equation of the two-wheeled vehicle is given by

$$\begin{bmatrix} \ddot{\delta} \\ \dot{\delta} \\ \ddot{\omega} \\ \dot{\omega} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} 0 & L_d & 0 & L_o & 0 \\ 1 & 0 & 0 & 0 & 0 \\ S_{dd} & S_d & S_{oo} & S_o & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & R_o & 0 \end{bmatrix} \begin{bmatrix} \dot{\delta} \\ \delta \\ \dot{\omega} \\ \omega \\ \theta \end{bmatrix} + \begin{bmatrix} 0 & L_{dt} \\ 0 & 0 \\ S_{ot} & S_{dt} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \omega_\tau \\ \delta_\tau \end{bmatrix}. \quad (1)$$

There is an assumption that the tire does not cause sideslip and that all angle is lower value. Here, δ is the roll angle, ω is the steer angle, θ is the direction angle, ω_τ is the steering torque, and δ_τ is the weight shift. The details of each parameter are given in the appendix.

Moreover, the Ackermann-Jeantaud turn theory can be applied to the two-wheeled vehicle (Figure 2). The conditional equation in kinematics based on the Ackermann-jeantaud turn theory then becomes:

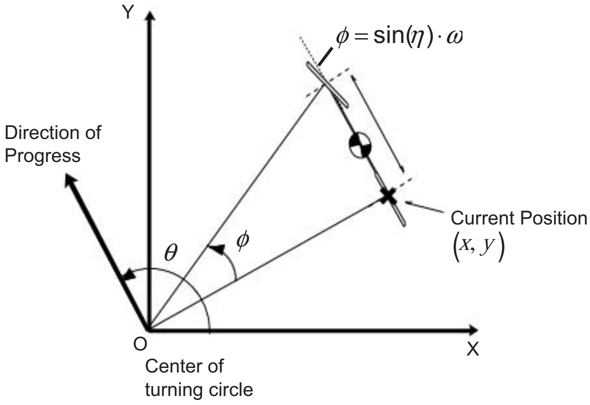

Fig. 2. Dynamics of Ackermann-Jeantaud

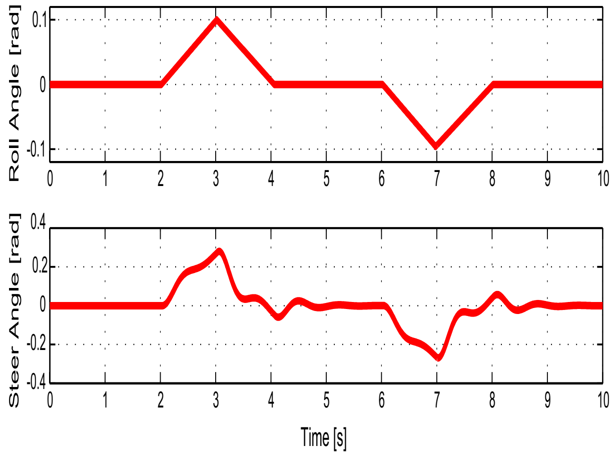

Fig. 4. Relation between the roll angle and the steer angle

$$\begin{aligned}\dot{x} &= v\cos(\phi)\cos(\theta),\\ \dot{y} &= v\cos(\phi)\sin(\theta),\\ \dot{\theta} &= \tfrac{v}{L}\sin(\phi),\end{aligned} \tag{2}$$

where (x, y) is the position, v is the velocity, ϕ is the actual steer angle, and L is the wheelbase. Equation (2) is used for the prediction of the future vehicle condition control and the reproduction of the motion of the vehicle at the simulation.

Therefore, this two-wheeled vehicle has three inputs (steering torque ω_τ, weight shift δ_τ, and velocity v) and four outputs (position (x,y), direction angle θ, and roll angle δ) and is a MIMO object (Figure 3).

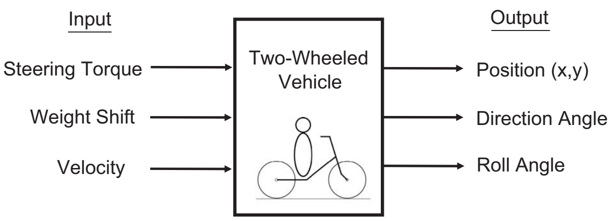

Fig. 3. MIMO of the two-wheeled vehicle

B. Self-steering of Two-wheeled Vehicle

The two-wheeled vehicle will not fall over while it is moving because of the self-steering mechanism that is incorporated into the steering system of the vehicle. Self-steering is a function employed when the vehicle turns in the direction that the vehicle is falling. A familiar example of this function is riding a bicycle with no hands.

The two-wheeled vehicle represented by equation (1) has the self-steering function. The operator is assumed to apply no torque to the handlebars (ω_τ=0), and his weight shift is the simple control (δ_τ=-$k_d\delta$). The relationship between the roll angle and the steer angle is shown in Figure 4. This result demonstrates self-steering toward the roll angle input.

III. Intelligent MIMO Control

A. Human MIMO Control Knowledge

The multiple inputs of the MIMO object are interrelated. One input influences some other inputs. It is difficult to find inputs that can be controlled appropriately because of this complex relationship; nevertheless, the expert can control a MIMO object given their knowledge of the interrelation between multiple inputs. The expert has the model between multiple inputs.

The skilled operator has knowledge of the interrelation between the handlebar operation input and the weight shift input. The operator knows the self-steering function, which is the model between multiple inputs. They do not need to apply excessive torque to the handlebars when operating the two-wheeled vehicle since, in the event excessive torque is applied to the handlebars, the effect of self-steering is disrupted. Handlebar operation is necessary only when a two-wheeled vehicle operates at reduced speeds and becomes unstable. When the vehicle operates at a certain velocity, it is important to lean the vehicle smoothly to optimize self-steering. The best operating method is for the operator to support the handlebars while relaxing their arms, and to lean the vehicle to turn.

Moreover, skilled operators select an appropriate target forward of the vehicle and move toward that target while considering the distances between the vehicle and any obstacles. Furthermore, skilled operators understand the running characteristic of the two-wheeled vehicle. Taken together, the skilled operator considers the following when operating a two-wheeled vehicle:

- knowledge of operation method
  - get the vehicle to lean skillfully and turn
  - support the handlebars, while relaxing the arms
- knowledge of surrounding condition judgment
  - reach target accurately as soon as possible
  - avoid obstacles in order to maintain safety
- knowledge of vehicle characteristic

– understand the running characteristic of one's own vehicle

While considering the running characteristic, skilled operators predict that 'if the vehicle is leaned to the right at a constant velocity, it will turn the corner'. Based on this prediction, the operator makes the vehicle lean and turns the corner.

B. *Intelligent MIMO Control System*

Here we propose an intelligent MIMO control (iMIMOc) system (Figure 5). The iMIMOc controller has human MIMO control knowledge and is used to control a two-wheeled vehicle, which is a MIMO object.

The iMIMOc controller consists of a predictive fuzzy control component and a detector component. The predictive fuzzy control component decides what operation to employ in a given situation. The detector component observes whether the vehicle will come into contact with obstacles and whether to reach the target. The detector is also responsible for selecting the subsequent target after arriving at the present target.

As described in Section III-A, the optimal method for operating a two-wheeled vehicle is not to operate the vehicle using the handlebars, but rather to lean the vehicle. When the operator can perform a natural weight shift, he/she can control the vehicle skillfully by leaning. However, it is difficult to actualize a natural weight shift. The roll angle is controlled by directly using an inertia rotor so that the operation method, which is to 'skillfully cause the vehicle to lean', is achieved. In short, the roll angle instruction is sent from the iMIMO controller to the two-wheeled vehicle instead of the weight shift instruction; the control instruction δ_{out} from the iMIMOc controller is sent, and the roll angle δ follows this δ_{out}.

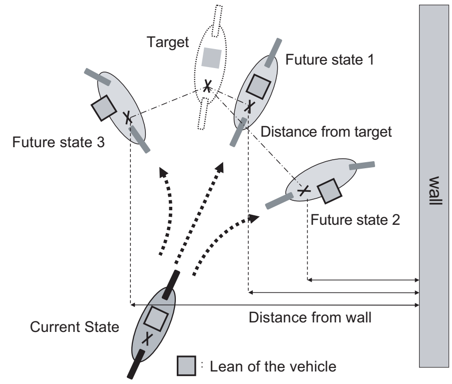

Fig. 6. Operation candidates with prediction

the features of this object, and to formulate the best control instruction based on the control rules [5].

Various control instructions, namely, 'maintain a constant velocity, support the handlebars while relaxing the arms, and keep the vehicle the upright', 'maintain a constant velocity, support the handlebars while relaxing the arms, and lean the vehicle to the right', and 'maintain a constant velocity, support the handlebars while relaxing the arms, and lean the vehicle to the left' are formulated. As shown in Figure 6, the future condition of the vehicle is predicted from the present condition of each controller candidate prepared. Using the predicted results for each controller candidate, the deflection from the target (distance and angle), the distance from the wall (forward, right side, and left side), and the magnitude of the change in the roll angle is evaluated by a fuzzy set. The best instruction with the highest evaluation is $Uout$. The process for deciding the best control instruction by the predictive fuzzy control is shown in Figure 7.

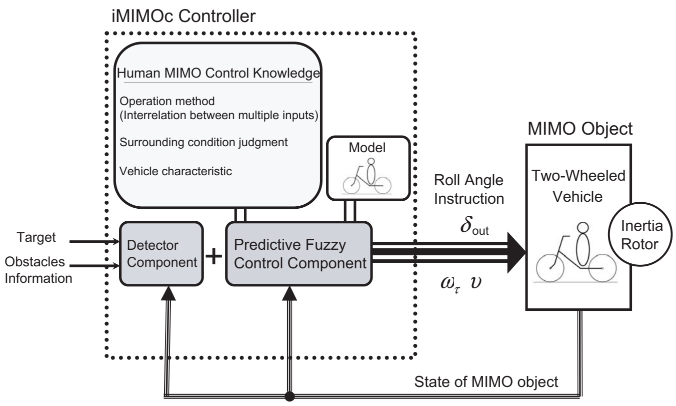

Fig. 5. System configuration

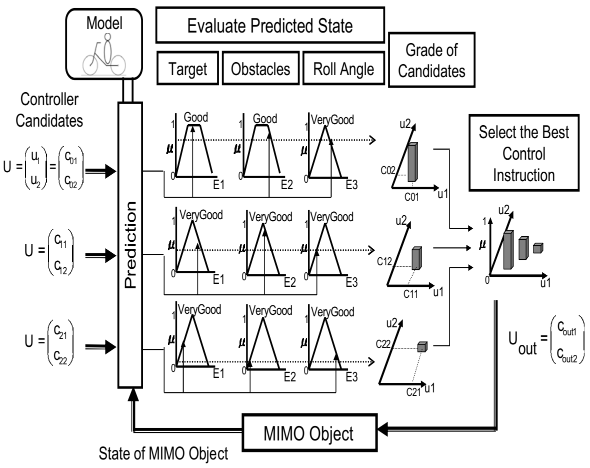

Fig. 7. Process of the iMIMOc

1) Intelligent MIMO Control Method: The control method employed for the iMIMOc expands the predictive fuzzy control to include the MIMO object. The predictive fuzzy control method is used to predict the future condition of the controlled object, to consider the substantial knowledge of

The predictive fuzzy control rule concerning the velocity, the steering torque, and the method for leaning the vehicle are as follows:

- IF(U = maintain a constant velocity, support the handlebars while relaxing the arms, and keep the vehicle the present roll angle ⟶ Target is *Good*, Obstacles is *Good*, Roll angle is *Good*) THEN U = maintain a constant velocity, support the handlebars while relaxing the arms, and keep the vehicle the present roll angle.
- IF(U = maintain a constant velocity, support the handlebars while relaxing the arms, and make the vehicle the upright ⟶ Target is *Good*, Obstacles is *Good*, Roll angle is *Good*) THEN U = maintain a constant velocity, support the handlebars while relaxing the arms, and make the vehicle the upright.
- IF(U = maintain a constant velocity, support the handlebars while relaxing the arms, and lean a little the vehicle to the right ⟶ Target is *Very Good*, Obstacles is *Very Good*, Roll angle is *Good*) THEN U = maintain a constant velocity, support the handlebars while relaxing the arms, and lean a little the vehicle to the right.
- IF(U = maintain a constant velocity, support the handlebars while relaxing the arms, and lean a little the vehicle to the left ⟶ Target is *Very Good*, Obstacles is *Very Good*, Roll angle is *Good*) THEN U = maintain a constant velocity, support the handlebars while relaxing the arms, and lean a little the vehicle to the left.
- IF(U = maintain a constant velocity, support the handlebars while relaxing the arms, and lean the vehicle to the right ⟶ Target is *Very Good*, Obstacles is *Very Good*, Roll angle is *Very Good*) THEN U = maintain a constant velocity, support the handlebars while relaxing the arms, and lean the vehicle to the right.
- IF(U = maintain a constant velocity, support the handlebars while relaxing the arms, and lean the vehicle to the left ⟶ Target is *Very Good*, Obstacles is *Very Good*, Roll angle is *Very Good*) THEN U = maintain a constant velocity, support the handlebars while relaxing the arms, and lean the vehicle to the left.
- IF(U = maintain a constant velocity, support the handlebars while relaxing the arms, and lean greatly the vehicle to the right ⟶ Target is *Very Good*, Obstacles is *Very Good*, Roll angle is *Very Good*) THEN U = maintain a constant velocity, support the handlebars while relaxing the arms, and lean greatly the vehicle to the right.
- IF(U = maintain a constant velocity, support the handlebars while relaxing the arms, and lean greatly the vehicle to the left ⟶ Target is *Very Good*, Obstacles is *Very Good*, Roll angle is *Very Good*) THEN U = maintain a constant velocity, support the handlebars while relaxing the arms, and lean greatly the vehicle to the left.

The fuzzy sets used for the control instruction decision are shown in Figure 8.

2) Inertia Rotor: The inertia rotor is an actuator that directly controls the roll angle of the vehicle and is an alternative to replace weight shifting. This actuator can

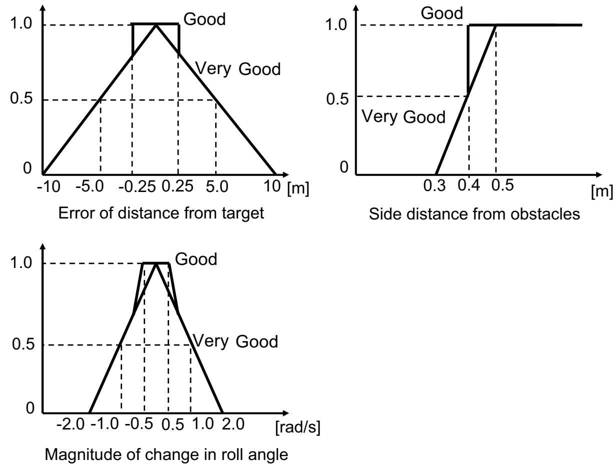

Fig. 8. The fuzzy sets used for the control instruction decision

control the roll angle by using the reaction torque generated when the rotor rotates [6]. The inertia rotor experimental apparatus for the roll angle control is shown in Figure 9. The inertia rotor stabilizes the two-wheeled vehicle even in an unstable condition such as a low-speed state or a stopped state. The inertia rotor can also realize a *static stop* of the two-wheeled vehicle.

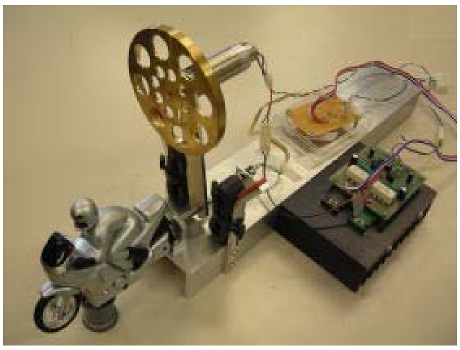

Fig. 9. The inertia rotor for the roll angle control

IV. Simulation Experiment

To confirm the effectiveness of the constructed intelligent MIMO control system, a simulation experiment using an actual course was performed.

A. Experiment Setup

The experimental track is an S-shaped course that consists of the first corner and the second corner. Targets are positioned in three locations: the exit of the first corner, the entrance of the second corner, and the exit of the second corner. The target located in the exit of the second corner is the goal target. The simulation finishes when the vehicle arrives at the goal target. For simplicity, the velocity is constant at 8 $[m/s]$.

The result obtained using the iMIMOc is compared with the results obtained using a conventional control. The conventional controller is a cascade PD controller (Figure 10). The method of operation for this controller is to operate the two-wheeled vehicle only in the steering control in roll angle fixation (δ=0). In other words, the vehicle (a bicycle with training wheels that cannot fall over) is moving toward the target.

The assumption of the iMIMOc facilitates complete control of the roll angle of the vehicle by the inertia rotor. The roll angle of the vehicle follows the roll angle instructions. Moreover, the operation 'support the handlebars while relaxing the arms' is achieved by ω_T=-$k_o\dot{\omega}$. That is, the arms of the operator work as a steering damper.

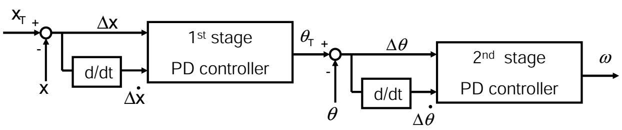

Fig. 10. the cascade PD control method

B. Experiment Result

The running trajectory of the conventional control is shown in Figure 11. The graph of the roll angle and the steer angle at that time is shown in Figure 12. The running time from the start point to the goal target was 5.8 $[sec]$.

The running trajectory of the iMIMOc is shown in Figure 13. The graph of the roll angle and the steer angle is shown in Figure 14. The running time was 5.2 $[sec]$.

C. Discussion

When the conventional control is used, the two-wheeled vehicle approaches the wall because the conventional control does not consider the distance of the vehicle from obstacles. In addition, the steer angle was frequently switched when running straight. This was thought to be due to the control method, which follows the target value as accurately as possible while evaluating the deflection between the target value and the present value.

Conversely, when the iMIMOc method is used, the vehicle is maneuvered optimally according to MIMO knowledge, and runs closer to the center of the course without approaching the wall. The arrival time from the start point to the final target is 0.6 $[sec]$ earlier than that achieved with conventional control. The two-wheeled vehicle begins to turn into each of the corners at 0.6 $[sec]$ and 3.1 $[sec]$. The steer angle vibrates after the vehicle turns because MIMO control knowledge is inadequate. Nonetheless, the results obtained by applying the iMIMOc to the two-wheeled vehicle are generally better than the results obtained by applying the conventional control.

V. Conclusions

In this paper, an intelligent MIMO control (iMIMOc) method, which was designed using human MIMO control knowledge, was proposed. The proposed method was applied to a two-wheeled vehicle, which is a typical MIMO object, and the following findings were confirmed from the simulation experiment: 1) An iMIMOc can be designed using

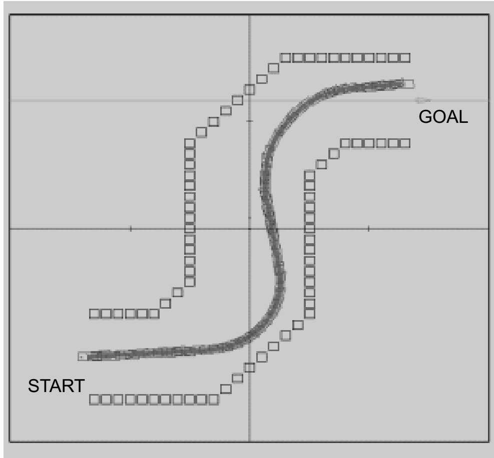

Fig. 11. the vehicle trajectory by the conventional control method

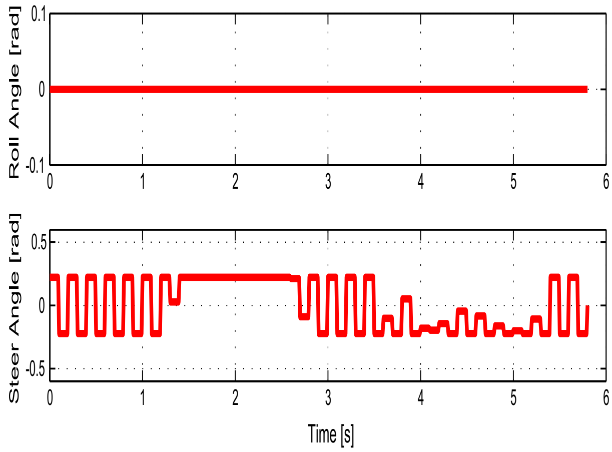

Fig. 12. roll angle - steer angle (the conventional control)

MIMO knowledge since it is possible to control the direction of such a vehicle by leaning, in the manner of a skilled operator, while adapting to the surrounding circumstances. As a result, the vehicle can run an S-shaped course. 2) The iMIMOc is an improvement over conventional control with respect to the trajectory followed and the arrival time.

Thus, the proposed iMIMOc is effective for controlling a two-wheeled vehicle. It was confirmed that the iMIMOc method built using human MIMO control knowledge was effective for an MIMO object that was considered difficult to control.

Appendix

The parameters of Figure 1 are

M : total mass [kg]
m : mass of human upper-body [kg]
g : gravity acceleration [N/kg]
h : height of COM (center of mass) from ground [m]
h_m : height of upper-body COM from COM [m]
I_e : moment of inertia around point C [kg-m^2]
η : π/2 - (the caster angle) [rad]
v : velocity [m/s]

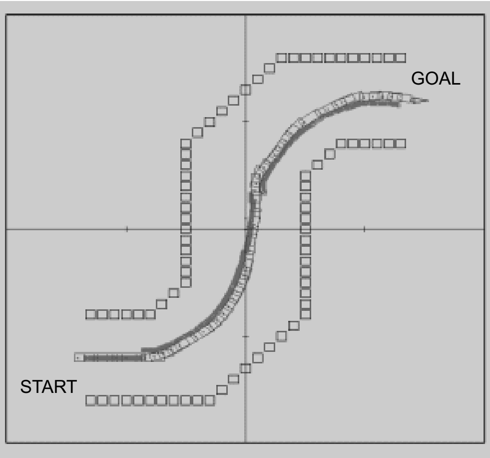

Fig. 13. the vehicle trajectory by iMIMOc method

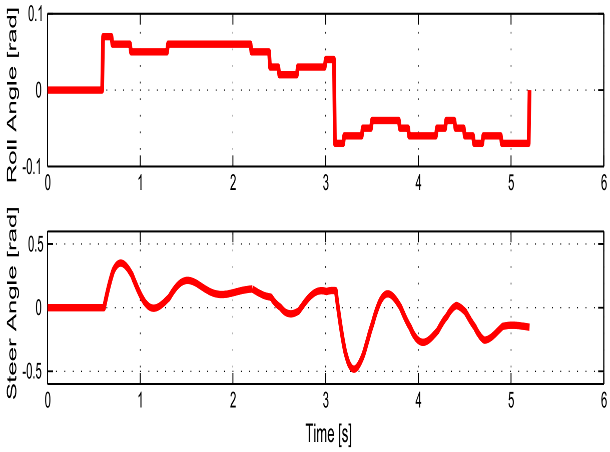

Fig. 14. roll angle - steer angle (the iMIMOc)

L : wheelbase [m].

The details of each parameter of equation (1) are given by

$$
\begin{aligned}
L_d &= Mgh/I_e,\\
L_o &= -(Mh/I_eL)v^2\sin(\eta),\\
L_{dt} &= (mg/I_e)(1 - Mh(h+h_m)/I_e),\\
R_o &= (v/L)\sin(\eta),\\
S_{dd} &= (\mu/\rho)v\sin(\eta),\\
S_d &= -\cos(\eta)L_d + \lambda^2(1-C_t)\tau,\\
S_{00} &= -(\sin^2(\eta)/L)v - 2\rho\lambda^2C_c(\sin(\eta)/v)\tau^2,\\
S_0 &= \sin(\eta)\cos(\eta)[1 + (2I_p/Mh\rho)(L_d/g)\\
&\quad - (\mu/\rho)]v^2/L - \{L_d\alpha\sin(\eta)\cos(\eta)(2\rho/h)\\
&\quad + \lambda^2[C_c\sin(\eta) - (1-C_t)\cos(\eta)]\}\tau,\\
S_{ot} &= 1/I_{xs},\\
S_{dt} &= -\cos(\eta)L_{dt},
\end{aligned}
$$

where

$$
\begin{aligned}
Mg\alpha\sin(\eta)/I_{xs} &= \lambda^2,\\
f/2\rho &= \tau,\\
I_p/I_{xs} &= \mu,
\end{aligned}
$$

and

α : ratio of the mass that the front wheel bears to the total mass
ρ : radius of the front wheel [m]
I_{xs} : moment of inertia around the steering axis [kg-m^2]
I_p : polar moment of inertia of the front wheel [kg-m^2]
C_c : cornering coefficient
C_t : camber coefficient
f : trail [m].

The values of each parameter were obtained from the literature [7][8].

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