

An Intelligent MIMO Control and Its Application to Two-wheeled Vehicle for Driving Support

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Abstract—A two-wheeled vehicle is a MIMO (Multiple-Input Multiple-Output) object. While it is difficult for a beginner rider to operate a two-wheeled vehicle, a skilled rider is able to operate the vehicle cleverly using human MIMO knowledge. In this paper, an intelligent 2-wheeled vehicle driving support (i2DS) system, which applies the intelligent MIMO control (iMIMOC) method that can be built using human MIMO knowledge, is proposed. Operation instructions from the i2DS system are accessibly presented to a user by using plural driving support interfaces. The effectiveness of this system is confirmed.

Index Terms—intelligent MIMO control (iMIMOC), human MIMO control knowledge, predictive fuzzy control, two-wheeled vehicle, driving support system

I. INTRODUCTION

The feature of the traffic accident concerning a two-wheeled vehicle (2WV) is that the ratio of a solo accident is higher than that of a four-wheeled vehicle. This is attributed not to only a traffic violation but also a beginner rider's unskillfulness of driving technique. In a word, the traffic accident decreases if a novice can operate a 2WV like a skilled rider. In addition, the novice is able to get amusement of maneuvering the 2WV at will by acquiring the driving skill.

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). An intelligent MIMO control (iMIMOC) method that can be built using human MIMO control knowledge had been applied to a 2WV that is a typical MIMO object, and the effectiveness of the iMIMOC has been confirmed [1][2].

In this paper, an intelligent two-wheeled vehicle driving support (i2DS) system that build using operation knowledge of a skilled rider constructed by applying the iMIMOC method is proposed. This i2DS system plainly presents supporting information by using two kinds of driving support interface, and supports a user. The effectiveness of the proposed i2DS system is evaluated by simulation experiment, and whether the iMIMOC can be applied to support of a MIMO object that humans operate is verified.

II. INTELLIGENT MIMO CONTROL

A. MIMO Knowledge of Skilled Operator

It is difficult to control a MIMO controlled object compared with a SISO (Single-Input Single-Output) controlled object usually. This is because the interrelation between multiple inputs of a MIMO object exists, as shown in Figure 1. This interrelation is a relation of influencing other input when one input is changed. It is hard to find inputs that can be controlled appropriately because of this complex relationship.

A skilled operator has knowledge of the interrelation between multiple inputs. The skilled operator understands whether if the method of what input is done the MIMO object can be controlled adequately, and he/she practices this method. As a concrete technique, a part of the MIMO object is first taken out without making all input method decided at a time, the input method taken out is considered, and decided. Another input is examined by using the decided input, and a final manner of operation is determined.

MIMO control knowledge, which is used by this paper, is defined as knowledge of the interrelation between multiple inputs of a MIMO object which a skilled operator has.

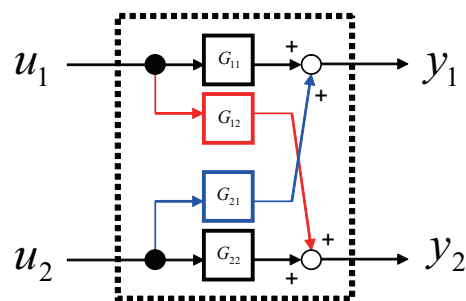


Fig. 1. Interrelation between multiple inputs of MIMO object

B. Intelligent MIMO Control Method

An intelligent MIMO control (iMIMOC) method built using MIMO knowledge of a skilled operator is shown in Figure 2. The control method employed for the iMIMOC expands a predictive fuzzy control [3] to include a MIMO object. The predictive fuzzy control method is used to predict the future condition of a controlled object and to consider substantial knowledge of the features of this object, and to formulate the

best control instruction based on the control rules. Firstly, in the predictive fuzzy control used as the iMIMOC, some input methods are fixed by an intelligent control, a simple feedback control, and so on, according to MIMO control knowledge. Secondly, future states are predicted from operation candidates, which are prepared from combination of decided inputs and candidates of other inputs, by using the model of the controlled object. Lastly, The best control order is decided by multipurpose fuzzy evaluation of their future states. The operation of a skilled operator in a MIMO controlled object can be achieved by using the iMIMOC method.

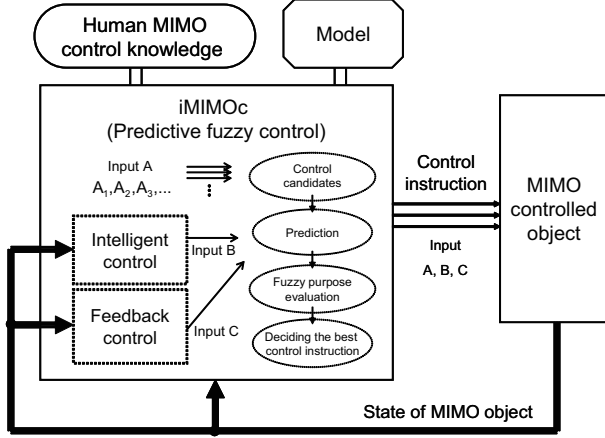


Fig. 2. Configuration of iMIMOC system

III. TWO-WHEELED VEHICLE

A. Rider - Two-wheeled Vehicle Object

A rider - two-wheeled vehicle (2WV) object, which is a typical MIMO object, is shown in Figure 3. The equations of motion of this controlled object are calculated from Lagrange's equation as well as Sharp [4], as shown in equations (1)~(12). These equations represent five degrees of freedom (DOF), namely, the lateral motion, the yaw motion, the roll motion, the steering motion and the longitudinal motion. Parameters of the vehicle were decided based on Bibliography [5], and this 2WV is assumed to be a motorcycle.

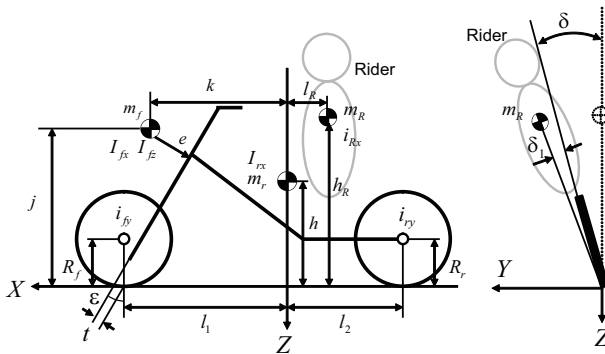


Fig. 3. Coordinates and symbols of rider - two-wheeled vehicle

- Equation to DOF of lateral direction

$$(M_f + M_r + m_R)(\ddot{y} + \dot{x}\dot{\theta}) + (M_f k - m_R l_R)\ddot{\theta} + (M_f j + M_r h + m_R h_R)\ddot{\delta} + M_f e \ddot{\omega} - Y_f - Y_r = 0 \quad (1)$$

- Equation to DOF of yaw angle

$$(M_f k - m_R l_R)(\ddot{y} + \dot{x}\dot{\theta}) + (M_f e k + I_{fz} \cos \varepsilon)\ddot{\omega} + (M_f k^2 + I_{rx} + I_{fx} \sin^2 \varepsilon + I_{fz} \cos^2 \varepsilon + i_{Rz} + l_R^2 m_R)\ddot{\theta} + \{M_f j k - l_R h_R m_R + (I_{fz} - I_{fx}) \sin \varepsilon \cos \varepsilon - C_{rxz}\}\ddot{\delta} - \frac{i_{ry}}{R_f} \sin \varepsilon \dot{x}\dot{\omega} - \left(\frac{i_{fy}}{R_f} + \frac{i_{ry} + i\lambda}{R_r}\right)\dot{x}\dot{\theta} - l_1 Y_f + l_2 Y_r - T_{zf} - T_{zr} = 0 \quad (2)$$

- Equation to DOF of roll angle

$$(M_f j + M_r h + m_R h_R)(\ddot{y} + \dot{x}\dot{\theta}) + (M_f e j + I_{fz} \sin \varepsilon)\ddot{\omega} + (tZ_f - M_f e g)\omega + (m_R h_R^2 + i_{Rx} + M_f j^2 + M_r h^2 + I_{rx} + I_{fx} \cos^2 \varepsilon + I_{fz} \sin^2 \varepsilon)\ddot{\delta} + (M_f j k - h_R l_R m_R - C_{rxz} + (I_{fz} - I_{fx}) \sin \varepsilon \cos \varepsilon)\ddot{\theta} - (M_f j + M_r h + m_R h_R)g\delta + \frac{i_{ry}}{R_f} \cos \varepsilon \dot{x}\dot{\omega} - \left(\frac{i_{fy}}{R_f} + \frac{i_{ry} + i\lambda}{R_r}\right)\dot{x}\dot{\theta} - T_{xf} - T_{xr} = WS \quad (3)$$

- Equation to DOF of steering angle

$$M_f e(\ddot{y} + \dot{x}\dot{\theta}) + (I_{fz} + M_f e^2)\ddot{\omega} + C_\omega \dot{\omega} + \sin \varepsilon + (tZ_f - M_f e g) \sin \varepsilon \omega + (M_f e j + I_{fz} \sin \varepsilon)\ddot{\delta} + (tZ_f - M_f e g)\delta - \frac{i_{fy}}{R_f} \cos \varepsilon \dot{x}\dot{\delta} + \frac{i_{fy}}{R_f} \sin \varepsilon \dot{x}\dot{\theta} + (M_f e k + I_{fz} \cos \varepsilon)\ddot{\theta} + tY_f - T_{zf} \cos \varepsilon - T_{xf} \sin \varepsilon = ST \quad (4)$$

- Equation to DOF of longitudinal direction

$$(M_f + M_r + m_R)\dot{x} = F_A \quad (5)$$

- Tyre force

$$Y_{f,r} = -C_{Ysf,r} \alpha_{f,r} + C_{Ycf,r} \delta_{f,r} \quad (6)$$

$$T_{zf,r} = C_{Zsf,r} \alpha_{f,r} + C_{Zcf,r} \delta_{f,r} \quad (7)$$

$$T_{xf,r} = C_{Xsf,r} \alpha_{f,r} - C_{Xcf,r} \delta_{f,r} \quad (8)$$

$$\alpha_f = \frac{\dot{y} + l_1 \dot{\theta} - t\dot{\omega}}{\dot{x}} - \cos \varepsilon \omega \quad (9)$$

$$\alpha_r = \frac{\dot{y} + l_2 \dot{\theta}}{\dot{x}} \quad (10)$$

$$\delta_f = \delta + \sin \varepsilon \omega \quad (11)$$

$$\delta_r = \delta \quad (12)$$

Therefore, state variables are the position (x, y) , the yaw angle θ , the roll angle δ and the steering angle ω . Inputs by the rider are the weight shift input WS , the driving torque F_A and the steering torque ST . In other words, this rider - 2WV controlled object is the MIMO object which has three inputs.

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.

IV. INTELLIGENT DRIVING SUPPORT SYSTEM

A. Driving Knowledge of Skilled Rider

The influence degree of each input had been researched because the method of inputs to a 2WV is complex [5][6]. As a result, it turned out that the steering torque and the weight shift input exert a great impact on dynamics of the directional control of a 2WV.

The skilled rider has knowledge of the interrelation between the handlebar operation input and the weight shift input, that is, the rider knows the self-steering function. They do not need to apply excessive torque to the handlebars when operating the 2WV since, in the event excessive torque is applied to the handlebars, the effect of self-steering is disrupted. The best operating method is for the operator to support the handlebars while relaxing their arms, and to lean the vehicle to turn by using an appropriate weight shift [7]. Moreover, the accelerator operation is decided according to the present situation of a vehicle. Besides, because the handlebars operation is a passive control, and the accelerator operation is a manipulation uniquely decided by the present state of one's own vehicle, these operation method are determined in first. The skilled rider settles the entire input method in consideration of the way of the decided operation.

Skilled riders select an appropriate target forward of the vehicle and move toward its target while considering the distances between the vehicle and any obstacles. Furthermore, skilled riders understand the running characteristic of the 2WV.

Taken together, the skilled rider considers the following when operating a 2WV:

- MIMO knowledge (knowledge of interrelation between multiple inputs)
 - get the vehicle to lean skillfully and turn by a natural weight shift
 - decide on the speed according to the present situation of one's own vehicle
 - support the handlebars, while relaxing the arms
- knowledge of surrounding condition judgment
 - set target on the direction in which the vehicle will move, and 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 riders predict that 'If it is the current situation, the vehicle is decelerated, and if the vehicle is leaned to the right, it will

turn the corner'. Based on this prediction, the rider makes the vehicle lean and adjusts the velocity and turns the corner.

The running method of clearing the curve by a skilled rider is shown in Figure 4.

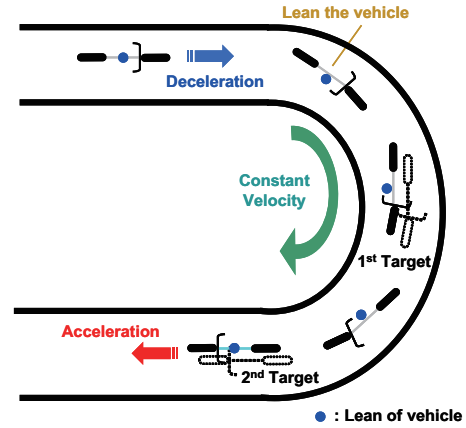


Fig. 4. Running method of curve by skilled rider

B. Intelligent Two-wheeled Vehicle Driving Support System

Here we propose an intelligent two-wheeled vehicle driving support (i2DS) system, which is constructed by applying the iMIMOC method, as shown in Figure 5. This i2DS system consists of the iMIMOC method and two kinds of driving support interfaces. The iMIMOC has 2WV operation knowledge of a skilled rider and is used to decide on reference control instructions. The decided control instructions are sent to driving support interfaces and are given to a user as driving support information. The user is able to operate a 2WV like a skilled rider, according to supporting information.

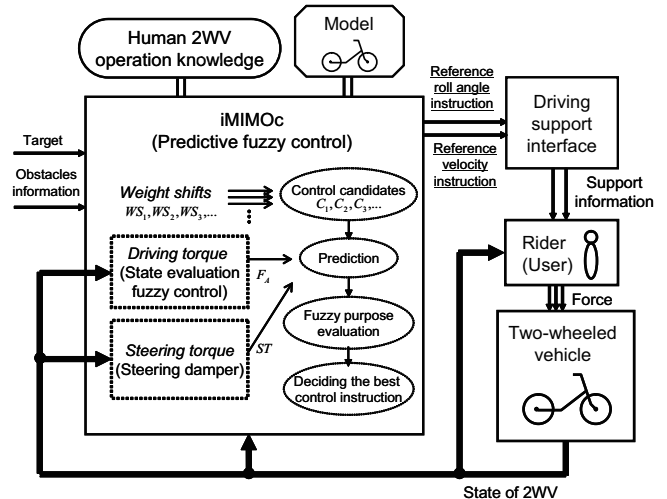


Fig. 5. Configuration of i2DS system

1) *Application of iMIMOC to Driving Support:* The reference roll angle and the reference velocity used for support information are calculated by the iMIMOC method. The control

method of the iMIMOC is a predictive fuzzy control that has skilled rider's 2WV driving knowledge. First of all, the driving torque F_A and the steering torque ST are decided according to MIMO control knowledge. Next, various control instructions about the weight shift input WS , namely, 'keep the vehicle the upright', 'lean the vehicle to the right', 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 by employing the model of the controlled object that has the decided inputs (F_A and ST). 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 sent to the driving support interface. The process for deciding the best control instruction by the predictive fuzzy control is shown in Figure 7.

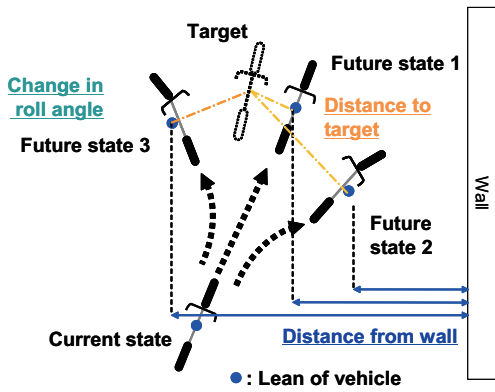


Fig. 6. Operation candidates with prediction

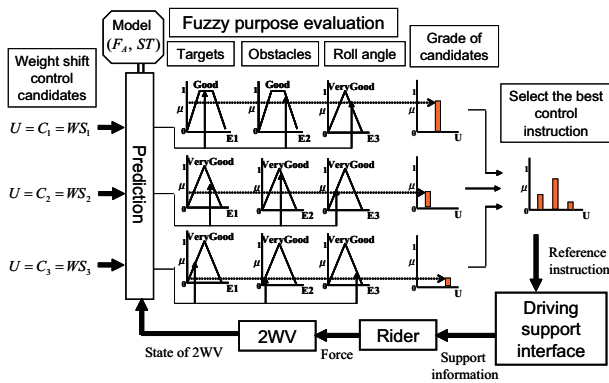


Fig. 7. Process of predictive fuzzy control as iMIMOC

The predictive fuzzy control rule concerning the method of multiple inputs are as follows:

- IF(U = follow the SEFC (State Evaluation Fuzzy Control) rule about the speed, support the handlebars while relaxing the arms, and keep the present roll angle → Target is *Good*, Obstacles is *Good*, Roll Angle is *Good*) THEN U = follow the SEFC rule about the speed, support the handlebars while relaxing the arms, and lean the vehicle to the right

U = follow the SEFC rule about the speed, support the handlebars while relaxing the arms, and keep the present roll angle.

- IF(U = follow the SEFC rule about the speed, 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 *Good*) THEN U = follow the SEFC rule about the speed, support the handlebars while relaxing the arms, and lean the vehicle to the right.
- IF(U = follow the SEFC rule about the speed, 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 *Good*) THEN U = follow the SEFC rule about the speed, support the handlebars while relaxing the arms, and lean the vehicle to the left.

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

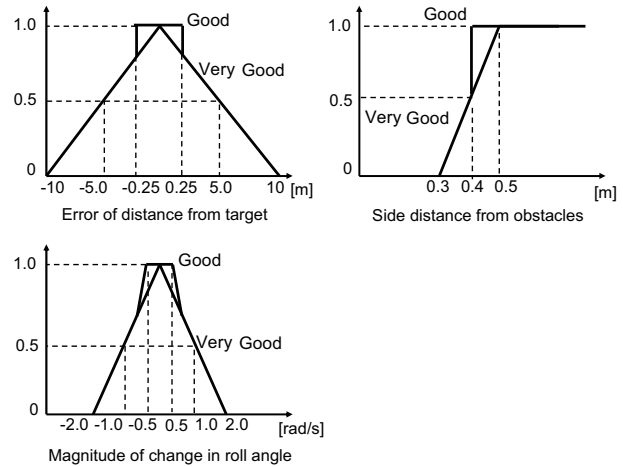


Fig. 8. Fuzzy sets used for control instruction decision

2) State Evaluation Fuzzy Control concerning Acceleration:

In the decision process of the control instruction of the iMIMOC, the driving torque F_A decided previously is obtained by a state evaluation fuzzy control [3]. The state evaluation fuzzy control rules concerning the speed control, namely, 'If the vehicle is almost upright and is near to a forward wall, decrease the speed.' and 'If the vehicle is almost upright and is far to a forward wall, increase the speed.' are prepared. Based on these control rules, the simple fuzzy inference gets executed concerning the state of the forward distance and the roll angle. Control instructions obtained from a number of control rules are integrated and applied the center of gravity defuzzification, and the driving torque is calculated. The process for deciding the control instruction by the state evaluation fuzzy control is shown in Figure 9.

The state evaluation fuzzy control rule concerning acceleration are as follows:

- IF the vehicle is almost upright AND near to a forward wall THEN U = decrease the speed.
- IF the vehicle is almost upright AND far to a forward wall THEN U = increase the speed.

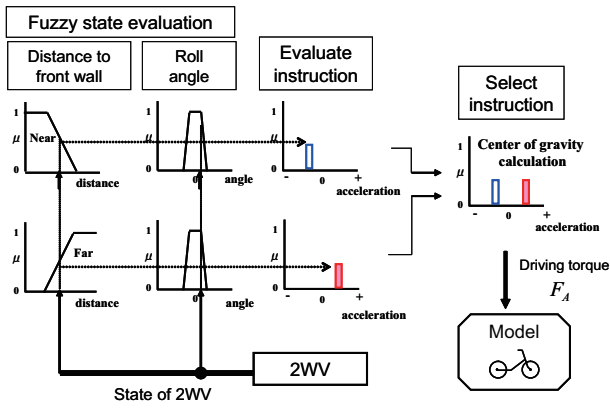


Fig. 9. Process of state evaluation fuzzy control for speed control

3) *Steering Damper*: The operation ‘support the handlebars while relaxing the arms’ of a skilled rider is achieved by

$$ST = K_d \dot{\delta} + K_o \dot{\omega}. \quad (13)$$

That is, the arms of the rider work as a steering damper [7]. This steering torque ST , which is given by equation (13), is used in the decision process of the iMIMOC.

4) *Driving Support Interface*: Two kinds of driving support interface, which are a speaker and vibration motors, are used to exhibit support information decided by the iMIMOC to a user plainly. The reference velocity instruction and the reference roll angle instruction are presented as sound information by a speaker and somatesthesia information by vibration motors respectively. As shown in Figure 10, this method can imitate the method of a instructor, which is a skilled rider, riding together on the 2WV and giving the pupil directions. The instructor gives the speed control instruction by his/her voice (“slow down!”, “speed up!”, etc.) ,and the instruction about how much the 2WV is leaned by applying force to his/her pupil. That is to say, human-friendly driving support is achieved by using these driving support interfaces. Moreover, the user is able to understand multiple supporting information easily by using different interfaces.

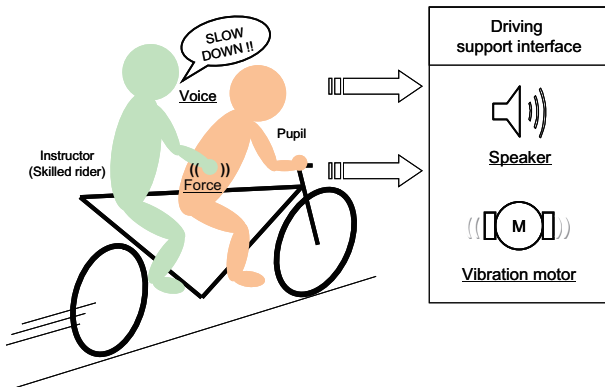


Fig. 10. Ideal driving supporting method by instructor and driving support interface as its alternative

V. SIMULATION EXPERIMENT

To confirm the effectiveness of the constructed i2DS system, a simulation experiment using an actual course was performed.

A. Driving Support Running by Virtual Rider

The experimental track has a course width of 7 [m] and a loose corner whose radius of turn is 45 [m]. The initial velocity is 60 [km/h], and the direction of movement is a clockwise direction. Targets are positioned in the front of the direction where the 2WV will move through. The simulation finishes when the vehicle arrives at the final target.

To evaluate the effect of the i2DS system quantitatively, a virtual rider is prepared instead of a real rider. The weight shift input of the virtual rider is WS which can make the reference roll angle perfectly. The driving torque is calculated by the proportion control concerning the velocity deflection and with the delay. The driving torque F_A is given by

$$F_A = K_v(v_{ref} - v) \frac{1}{T_v s + 1}. \quad (14)$$

The steering torque of the virtual rider is given by equation (13), where a rider steers in the direction where the 2WV falls over automatically so as not to go over; therefore, $K_d, K_o \geq 0$.

B. Experiment Result

The running trajectory of the i2DS system by the virtual rider is shown in Figure 11. The graph of the velocity and the roll angle at that time is shown in Figure 12. The running time from the starting point to the goal point was 9.6 [sec], the time in the point A was 1.8 [sec], and the time in the point B was 7.8 [sec].

C. Discussion

The 2WV decelerates rightly from the starting point to the entrance of the curve (point A), goes around the curve at the constant speed about 40 [km/h], accelerates gradually from the exit of the curve (point B) and runs. The vehicle is maneuvered optimally according to knowledge of a skilled rider, and runs closer to the center of the course without striking wall. As a consequence, the running method of the skilled rider, which was described in section IV-A, is able to be achieved. Although there are sort of vibrations in the roll angle, the result obtained by the virtual rider with the i2DS system is generally good. As future tasks, it is necessary to verify the experiment in various courses, and the driving support running by an actual user by using driving support interfaces.

The effectiveness of the i2DS system, which is constructed by applying the iMIMOC, was confirmed by this simulation experiment.

VI. CONCLUSIONS

In this paper, an intelligent MIMO control (iMIMOC) method, which has MIMO control knowledge of a skilled operator, was worked for an intelligent two-wheeled vehicle driving support (i2DS) system that was built using human

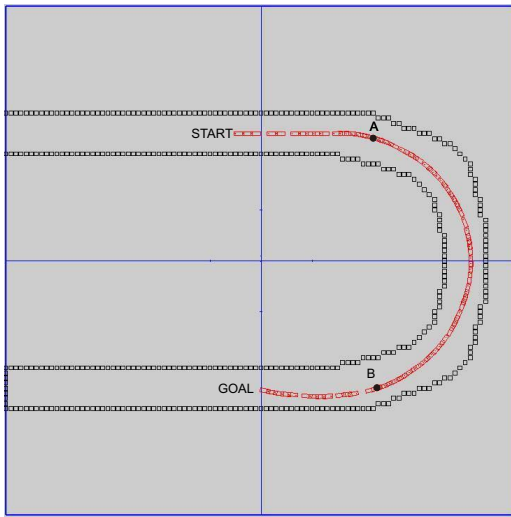


Fig. 11. Vehicle trajectory by virtual rider with i2DS system

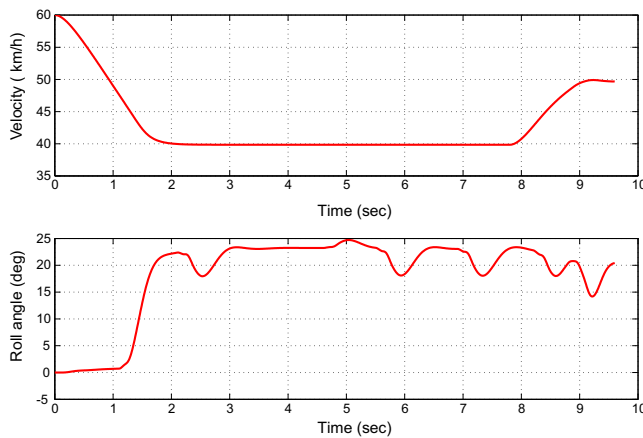


Fig. 12. Velocity and roll angle of 2WV

2WV operation knowledge. The following findings were confirmed from the simulation experiment by a virtual rider: An iMIMOC method can be built into a MIMO control knowledge of a skilled operator. This iMIMOC is applied, and an i2DS system built using 2WV driving knowledge of a skilled rider is constructed. As a result, it is possible to control the direction of such a vehicle by leaning and speed adjustments, in the manner of a skilled rider, while adapting to the surrounding circumstances.

Thus, the proposed i2DS system is effective as driving support of a 2WV. It was confirmed that the iMIMOC, which has MIMO control knowledge of a skilled operator, was able to be applied to human operation support.

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