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Proposal of Personal Mobility Vehicle Based on Stabilization Control of Two-Wheel Steering and Two-Wheel Driving

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ABSTRACT

Mobility in a city is an important part of our life. For the sustainable development, there should be a mobility which is friendly for human and environment. Recently, as a new mean, a personal mobility vehicle (PMV) which is compact and convenient has attracted attention. As a PMV, the following features should be considered. 1. To make short range transport be efficient and comfort by using low-impact actuator, 2. To be used safely in non-exclusive space for pedestrians, 3. To be enough compact to achieve seam-less transit with existing public transportation. A bicycle is the one of PMVs. It becomes unstable at low speed. The smaller the tire diameter becomes, less stable it becomes. The authors propose a stabilized vehicle with two-wheel steering and two-wheel driving (2WS/2WD) that solves the problem. The stability of the conventional bicycle has been discussed in a lot of papers; however, the study about the stability and control of the 2WS/2WD bicycle has not been investigated so much. In this paper, the stabilization of 2WS/2WD bicycle is shown and the new bicycle based on the simulation is suggested.

The authors propose the stabilization of the bicycle using driving forces and design a controller using linear-quadratic control theory. It is shown that by increasing the front and rear steering angle, the required moving distance for the forward direction for stabilization becomes smaller. The condition of the steering angle 90 degree corresponds to the parallel two-wheel vehicle. Finally, a new PMV for this result is proposed. The concept of PMV that authors propose consists of two modes, the bicycle mode and the parallel two-wheel mode. These two modes are convertible each other. It will be an effective mobility with low energy consumption by switching between two modes. In addition to the hybrid type PMV up above; we proposed the two-wheeled inverted pendulum vehicle moved by human pedaling that consists of the stabilization control by the in-wheel motors and the driving power by a human.

Keywords: Vehicle dynamics, Stabilization control, Personal Mobility Vehicle, Bicycle.

1 INTRODUCTION

For the sustainable development, it has been noted that spaces such as streets, sidewalks and facilities that are important in daily life need to be reconstructed in a practical and environmentally friendly manner. In contemporary Japan in particular, inbound traffic congestion in metropolitan cities decreases transportation efficiency and deteriorates the city environment via air pollution and noise. A new vehicle that is practical and environmentally friendly is required. Recently, a personal mobility vehicle (PMV), which is a vehicle suitable for personal use, has become available [1,2]. It moves at low speed and is sufficiently small that it can be used for travel in pedestrian space. Considering the usage of PMVs on streets and sidewalks and inside facilities, stability at low speed and a pedestrian affinity for the PMV is important. Although the PMV needs electrical power, the amount of consumed power is far smaller than that for a typical automobile. For a PMV, the following features should be considered. 1) Short range transportation should be efficient and comfortable using a low-impact actuator. 2) The PMV should be safe to use in non-exclusive pedestrian space. 3) The PMV should be sufficiently compact to achieve seamless coexistence with existing public transportation. The proposed PMV is expected to achieve greater convenience in the use of public transportation when combined with the use of trains. If such a PMV is developed, a person can use the PMV from his/her home to a nearby station and take a train with the PMV folded. At the arrival station, he/she unfolds the PMV and uses it to the destination. Such a convenient transportation system in a city promotes not only smoother traffic but also provides a solution to the problem of bicycle parking around stations [3]. In this paper, the authors propose the stabilization of the bicycle using driving forces and design a controller using linear-quadratic control theory. Using the results of the basic dynamics of two-wheel steering and two-wheel driving (2WS/2WD), a new concept of the PMV is proposed.

2 TWO-WHEEL STEERING AND TWO-WHEEL DRIVING BICYCLE

In this study, for the basic investigation of the bicycle, a bicycle that steers and drives both the front and rear wheels is considered. Motion dynamics and experiments show that a bicycle is unstable, especially when its speed is low, and a bicycle with small tires is less stable than one with larger ones[4]. In terms of the PMV, which is to be used in walking spaces, however, it is necessary for the bicycle to be driven stably at low walking speeds. It is also necessary for the bicycle to have small tires so that it occupies a small space in walking spaces and is compact enough to be carried.

Previous research into increasing the stability of the bicycle is as follows. One design aspect is the parametric adjustment of the bicycle such as changes in the tire diameter, head angle and offset [5]. Another is the steering of the rear wheel [6]. When the vehicle steers the rear wheel in the same direction as that of the front wheel, the gyration radius becomes large and the straight ahead stability increases. When the vehicle steers the rear wheel in the opposite direction to that of the front wheel, the gyration radius becomes small and tight turning is achieved. However, the restrictions of the design parameters considering the trail effect and the front weight effect may possibly restrain the development of a compact PMV, and there is a limit to the increase in stability using only parametric adjustments. The adjustment of the rear steering is effective when the bicycle is traveling at a certain speed; however, this speed is not always suitable for the concept of the PMV, which must be able to travel at walking speed. Therefore, in this paper, the authors investigate stabilization using the driving forces of the front and rear wheels as in the parallel two-wheel mode. The two-wheel steering and two-wheel driving bicycle with driving forces is considered to be the model for improving stability.

3 MODELING AND CONTROL

The model of the bicycle is shown in Figs. 1–3, where m is the mass of bicycle, I_θ is the inertia of the bicycle in the roll direction, I_ϕ is the inertia of the bicycle in the yaw direction, h is the height of thecenter of gravity, l_f is the length between the front wheel and the center of gravity and l_r is the length between the rear wheel and the center of gravity as shown in Fig. 3. A moving coordinate system is adopted. To consider a steering system that is not influenced by parametric design, here, the head angle is defined to be 90 degrees and the offset is zero.The roll angle θ is assumed to be small and the bicycle is considered to be traveling at low speed, almost at a stop. The equations of motion of the bicycle are as follows.

$$m\ddot{x} = F_f \cos\delta_f + F_r \cos\delta_r \quad (1)$$

$$m\left(\ddot{y} + h\ddot{\theta}\right) = F_f \sin\delta_f + F_r \sin\delta_r \quad (2)$$

$$I_\phi \ddot{\phi} = -l_f F_f \sin\delta_f + l_r F_r \sin\delta_r \quad (3)$$

$$I_\theta \ddot{\theta} = mgh\theta - F_f \sin\delta_f h - l_r F_r \sin\delta_r h \quad (4)$$

Stabilization control is performed by using the driving forces of the front and rear wheels F_f and F_r, . Ignoring equation (1), which describes the motion in the forward–backward direction, equations (2)–(4) are defined as the plant of the control object. The state variable is

$$X = [y, \phi, \theta, \dot{y}, \dot{\phi}, \dot{\theta}]^T \quad (5)$$

To remove the nonlinear term, the control input is defined as $F_f(\sin\delta_f)^{-1}$ and $F_r(\sin\delta_r)^{-1}$. The feedback gain is obtained from linear-quadratic control theory. The evaluation function is

$$J = \int_0^\infty \left(X^T Q X + u^T R u\right) dt \quad (6)$$

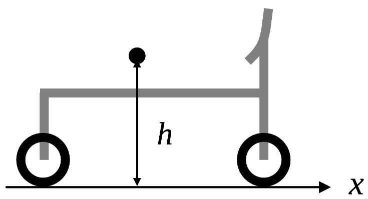


Figure 1. **Side view**

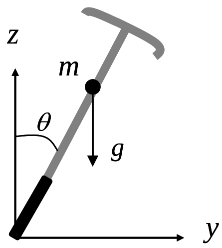


Figure 2. **Back view**

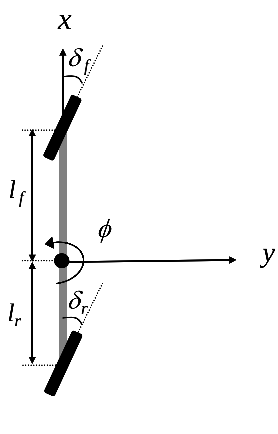


Figure 3. **Top view**

The driving force for the stabilization of the bicycle is

$$\begin{bmatrix} F_f \\ F_r \end{bmatrix} = \begin{bmatrix} \dfrac{1}{\sin\delta_f} & 0 \\ 0 & \dfrac{1}{\sin\delta_r} \end{bmatrix} \left(-GX\right) \tag{7}$$

4 SIMULATION RESULTS

Using the formulation, the results of numerical simulation are obtained. In the numerical simulation, the effect of the controller in stabilizing the bicycle in the upright position is confirmed. Table 1 shows the parameter values for the bicycle. The initial position of the bicycle is at the origin and the initial roll angle is 1 degree. Without control, the bicycle falls under the initial condition. Figure 4 shows the trajectory of the center of gravity of the bicycle at a steering angle ratio

$$\gamma=\delta_f/\delta_r=1 \quad , \tag{8}$$

and a front steering angle δ_f of 10 degrees. It is expressed in the inertial coordinate system. Figure 5 shows the time history of the roll angle, yaw angle and driving force. The weighting of the optimal control is

$$Q=\mathrm{diag}[10^8\ \ 10^8\ \ 10^2\ \ 1\ 1\ 1] \tag{9}$$

It is shown that the bicycle is stabilized while moving back and forth. When the bicycle moves back and forth, the driving forces also produce sideways forces for stabilizing the bicycle. In the same way, the steering angle ratio γ is set for several conditions as follows. Figures 6–7 show the simulation results for the bicycle at $\gamma = 1/2$, at which the rear steering angle is half the front steering angle. Figures 8–9 and Figs. 10–11 show simulation results for the bicycle at $\gamma = -1$ and -1/2, respectively, at which the rear steering angles are in the opposite direction to that of the front steering angle.

At $\gamma = 1/2$ as in Fig. 6, the movement of the bicycle in the forward–backward direction is larger than that at $\gamma = 1$. This means the steering angle of the rear wheel is smaller than that of the front wheel at $\gamma = 1/2$; therefore, the rear wheel needs to output more driving force to output the sideways force for stabilizing the bicycle. The larger driving force leads to larger movement in the forward–backward direction. In the case of $\gamma = -1$ as shown in Fig. 8, the movement of the bicycle is less than that for $\gamma = 1$. Figure 9 shows the driving force of the rear wheel is generated in the opposite direction to that for the case of $\gamma = 1$. In the case of negative phase ($\gamma = -1$), by setting the direction of the rear wheel driving force as opposite to the direction of the front wheel driving force, the side force direction is the same as that of the front wheel and the resultant force stabilizes the bicycle. As for the forward–backward direction, in the case of positive phase, the driving forces of the front and rear wheels are in the same direction and they are summed; the bicycle then moves in the forward–backward direction. In the case of negative phase, the driving forces of the front and rear wheels are in opposite directions; the movement in the forward–backward direction is minimized. At $\gamma = -1/2$ as shown in Fig. 10, the direction of the driving forces of the front and rear wheels are oppositely the same as at $\gamma = -1$. However, the movement in the forward–backward direction increases owing to the smaller steering angle of the rear wheel. The rear wheel needs to output more driving force to output the sideways force for stabilization of the bicycle.

Table 1. Parameter values for the bicycle

Description	Value
Mass of bicycle (m)	77.5 kg
Inertia of bicycle in roll direction (I_θ)	6.375 kgm^2
Inertia of bicycle in yaw direction (I_ϕ)	4.215 kgm^2
Height of center of gravity (COG) (h)	0.85 m
Length from front wheel to COG (l_f)	0.609 m
Length from rear wheel to COG (l_r)	0.304 m
Acceleration of gravity (g)	9.8 m/s^2

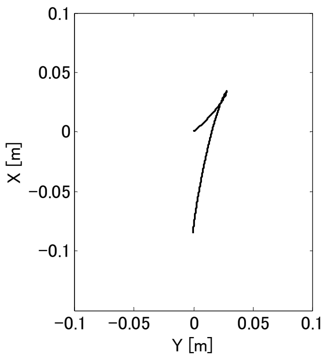


Figure 4. Trajectory at δ_f = 10 degrees and γ = 1

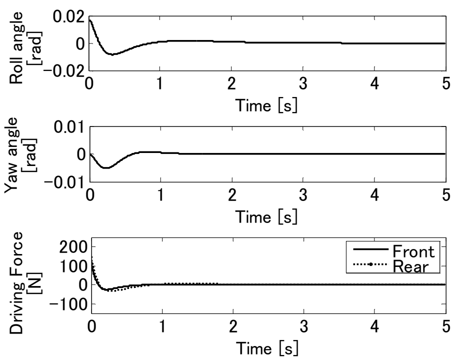


Figure 5. Roll, yaw and driving forces at δ_f = 10 degrees and γ = 1

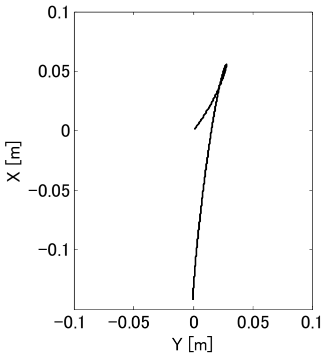


Figure 6. Trajectory at δ_f = 10 degrees and γ = 1/2

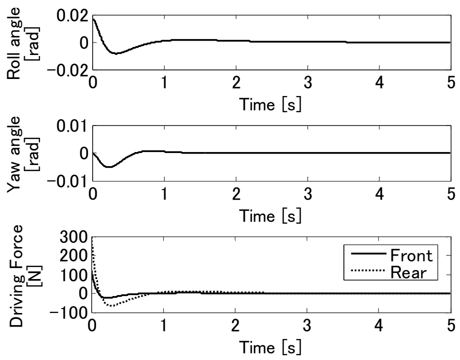


Figure 7. Roll, yaw and driving forces at δ_f = 10 degrees and γ = 1/2

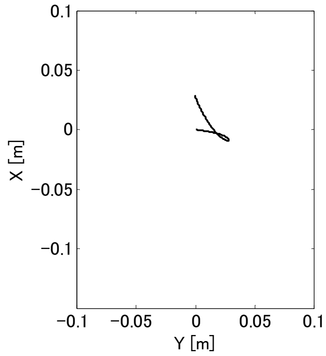


Figure 8. Trajectory at δ_f = 10 degrees and γ = -1

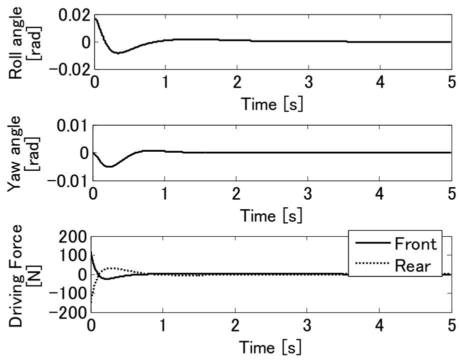


Figure 9. Roll, yaw and driving forces at δ_f = 10 degrees and γ = -1

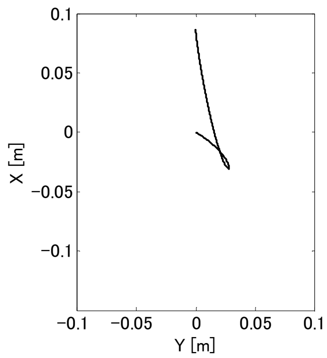


Figure 10. Trajectory at δ_f = 10 degrees and γ = -1/2

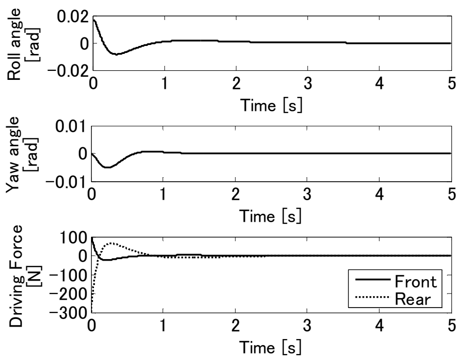


Figure 11. Roll, yaw and driving forces at δ_f=10 degrees and γ=-1/2

Next, the front steering angle is increased. Figures 12 and 13 show the case of the front steering angle δ_f = 30 degrees and γ = -1. Compared with the case of the steering angle of 10 degrees, the movement in the forward–backward direction and the driving forces decrease.
In the same way, for γ = 1 and -1, the front steering angle changes from 5 to 85 degrees. Figure 14 is a plot of the maximum moving distance in the *x* direction and Fig. 15 shows the maximum driving force. The maximum driving forces at γ = 1 and -1 are the same. We observed that by increasing the front and rear steering angles, the required moving distance in the *x* direction for stabilization decreases.

We also found that the condition of a steering angle of 90 degrees corresponds to the parallel two-wheel vehicle. In this case, the equations of motion (1) to (4) correspond to the equations of an inverted pendulum.

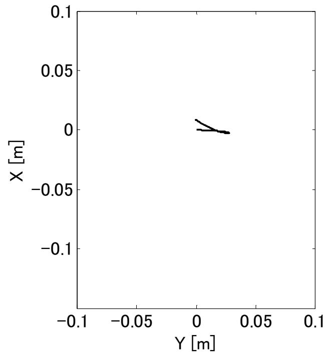


Figure 12. Trajectory at δ_f = 30 degrees and γ = -1

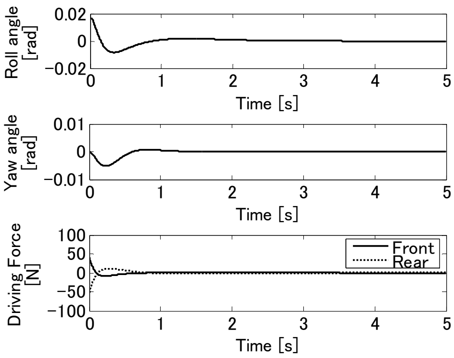


Figure 13. Roll, yaw and driving forces at δ_f = 30 degrees and γ = -1

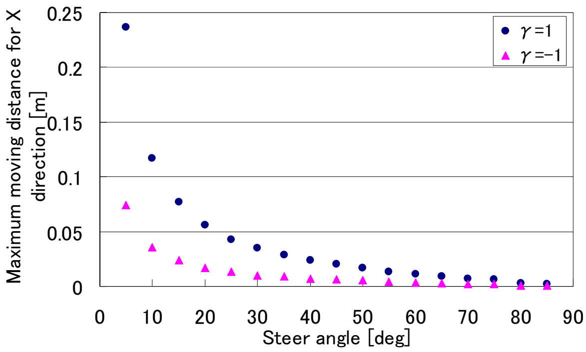


Figure 14. Maximum moving distance

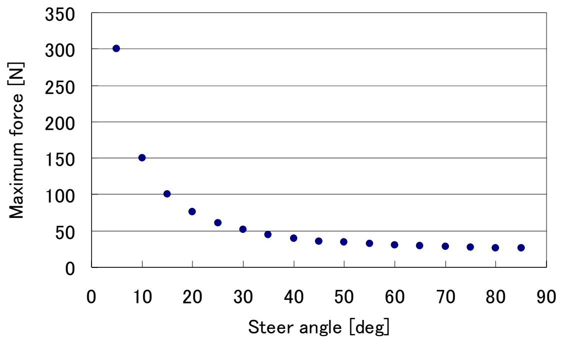


Figure 15. Maximum driving force

5 PROPOSAL OF PERSONAL MOBILITY VEHICLE

5.1 Hybrid type PMV

From the simulation results of the 2WS/2WD bicycle, it was shown that using the parallel two-wheel vehicle that is equal to the inverted pendulum system at low speed was effective in terms of its stability. Therefore, the concept of the PMV which we propose consists of two modes, the bicycle mode and the parallel two-wheel mode as shown in Figs. 16 and 17. This vehicle has four electric motors, two for driving and two for steering, and one generator connected to the pedals. These two modes are convertible to each other. In the bicycle mode, the rider rotates the pedals to generate electric power, and then the motors in the wheels produce torque using the generated energy. To combine human power and electric power for an efficient ride, the electric generator generates electricity from pedaling and the energy is stored in the battery. The generated electricity drives the drive motors of the front and rear wheels. Thus by abolishing a conventional chain, we achieve a drive-by-wire system. The front and rear steering are controlled by a steer-by-wire system. The parallel two-wheel mode is set up by folding the frame of the bicycle mode. The front and rear wheels in the bicycle mode are controlled, respectively. A driver stands on the step of the supporting frame of the wheels and the vehicle is controlled according to the movement of the center of gravity. The theory of the stabilization control for the inverted pendulum is used. Finally we had design validation of deformation mechanics by producing mock-up shown in Figs. 18 and 19.

Figure 16. Bicycle mode

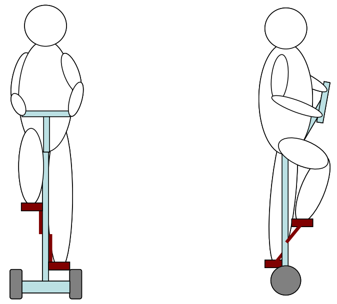
Figure 17. Parallel two-wheel mode

Figure 18. Mock-up of the Bicycle mode

Figure 19. Mock-up of the Parallel two-wheel mode

5.2 Parallel two-wheeled inverted pendulum vehicle moved by human pedalling

The proposal of another new type PMV is the parallel-two wheel mode that combines the human power and the electric power. The basic concept of the two-wheeled inverted pendulum vehicle moved by human pedaling consists of the stabilization control by the in-wheel motors and the driving power by a human. The two-wheeled inverted pendulum vehicle moved by human pedaling has the following benefits. Using the human power by pedaling for driving the vehicle makes the battery to be used for longer time. It is friendlier to the environment and energy saving compared with that of conventional inverted pendulum vehicle. Adding the pedal makes a human to exercise his/her foots and it is good for health. A driver sits on the saddle and it enables him/her to use the vehicle longer time than the stand-up ride type vehicle. The inverted pendulum vehicle with the pedal has good compatibility with the bicycle mode which we proposed. It is considered as the similar category of the conventional electric assist bicycle and has possibility to be used at public roads in Japan. Thus, the two-wheeled inverted pendulum vehicle with human pedaling is the vehicle that basically needs human power, so that it has the benefits in terms of the energy and health. Figure 20 shows the sketch of the two-wheeled inverted pendulum vehicle moved by human pedaling. Figure 21 shows the prototype vehicle.



(a) Front view (b) Side view

Figure 20. Parallel two-wheeled inverted pendulum vehicle moved by human pedaling

Figure 21. Prototype vehicle of the two-wheeled inverted pendulum vehicle moved by human pedaling

6 CONCLUSION

In this paper, the stabilization method of two-wheel steering and two-wheel driving (2WS/2WD) bicycle was analyzed. The tendency of stability of the 2WS/2WD bicycle with the control of driving forces was examined. It was shown that the 2WS/2WD bicycle at low speed is stabilized at each steering angle. The steering angle of more than around 30 degree achieves the stabilization control with small driving force. It was also found that the condition of a steering angle of 90 degrees corresponds to the parallel two-wheel vehicle.

From the simulation results, we proposed the PMV that consists of two modes, the bicycle mode and the parallel two-wheel mode. In addition to this hybrid type PMV, we showed the parallel-two wheel mode that combines the human power and the electric power.

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