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Stabilization of a bicycle with two-wheel steering and two-wheel driving by driving forces at low speed †

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Abstract

Recently, the personal mobility vehicle (PMV), a vehicle suitable for personal use, has been developed. It moves at low speed and is sufficiently small that it can be ridden in pedestrian space. This vehicle is expected to be a new method of transportation that is practical and environmentally friendly. As one form of PMV, the authors propose a two-wheel vehicle with two modes: a two-wheel steering and two-wheel driving bicycle mode and a parallel two-wheel mode. This vehicle has four electric motors, two for driving and two for steering, and one generator connected to the pedals. In the bicycle mode, the rider rotates the pedals to generate electric power, and the motors in the wheels produce torque using the generated energy. The front and rear wheels are steered by the electric motor according to the angle of the handle. Therefore, this bicycle is controlled by a steer-by-wire and a drive-by-wire system. In the parallel two-wheel mode, the vehicle is stabilized according to the theory of the inverted pendulum. In this paper, we focus on the bicycle mode and analyze its stability. Stabilizing the bicycle is not easy since the proposed vehicle has tires with small diameters and the traveling speed is assumed to be low. It is known that the stability of bicycles is tuned by adjusting the bicycle parameters and changing the rear steer angle. However, since we aim to use the vehicle in a narrow walking space at low speed, such conventional methods are not always suitable. The authors propose the stabilization of the bicycle using driving forces and design a controller using linear-quadratic control theory. The results of the numerical simulations show the proposed method is effective in stabilizing the bicycle.

Keywords: Bicycle; Personal Mobility Vehicle; Stabilization control; Vehicle dynamics

1. Introduction

In terms of 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

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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, a new concept of the PMV is proposed and its basic dynamics are analyzed.

2. PMV

2.1 Concept

The concept of the PMV the authors propose consists of two modes, the bicycle mode and the parallel two-wheel mode as shown in Figs. 1 and 2. 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.

Fig. 1. Bicycle mode.

Fig. 2. Parallel two-wheel mode.

2.2 Two-wheel steering and two-wheel driving bicycle

In this study, for the basic investigation of the bicycle mode, 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. 3–5, 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 the center 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. 5. 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.

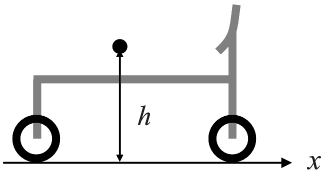

Fig. 3. Side view.

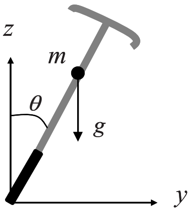

Fig. 4. Back view.

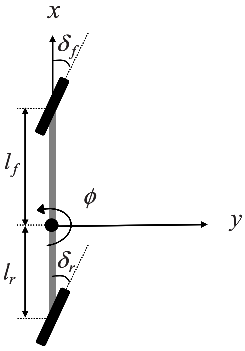

Fig. 5. Top view.

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.

$$m\ddot{x} = F_f \cos\delta_f + F_r \cos\delta_r \tag{1}$$

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

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

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

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

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

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

$$J = \int_0^\infty \left(X^T QX + u^T Ru \right) dt \tag{6}$$

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.

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 due to gravity (g)	9.8 m/s^2

Fig. 6 shows the trajectory of the center of gravity of the bicycle at a steering angle ratio

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

and a front steering angle δ_f of 10 degrees. It is expressed in the inertial coordinate system. Fig. 7 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. Figs. 8–9 show the simulation results for the bicycle at γ = 1/2, at which the rear steering angle is half the front steering angle. Figs. 10–11 and Figs. 12–13 show simulation results for the bicycle at γ= -1 and -1/2, respectively, at which the rear steering angles are in the opposite direction to that of the front steering angle.

At γ= 1/2 as in Fig. 8, the movement of the bicycle in the forward–backward direction is larger than that at γ= 1. This means the steering angle of the rear wheel is smaller than that of the front wheel at γ= 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 γ= -1 as shown in Fig. 10, the movement of the bicycle is less than that for γ= 1. Fig. 11 shows the driving force of the rear wheel is generated in the opposite direction to that for the case of γ= 1. In the case of negative phase (γ= -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.

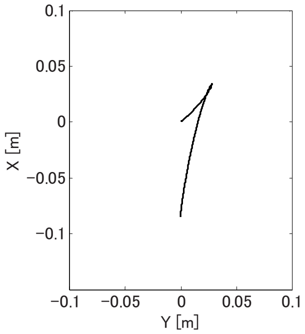

Fig. 6. Trajectory at δ_f= 10 degrees and γ= 1.

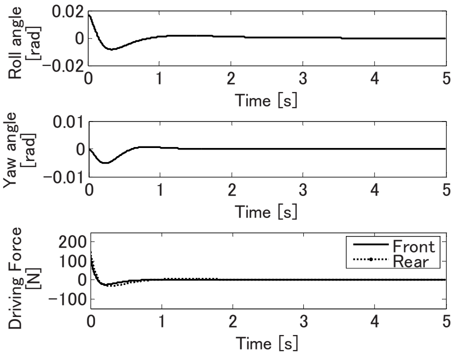

Fig. 7. Roll, yaw and driving forces at δ_f= 10 degrees and γ= 1.

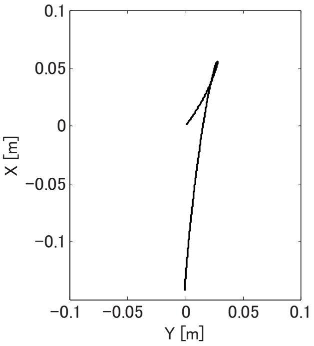

Fig. 8. Trajectory at δ_f= 10 degrees and γ= 1/2.

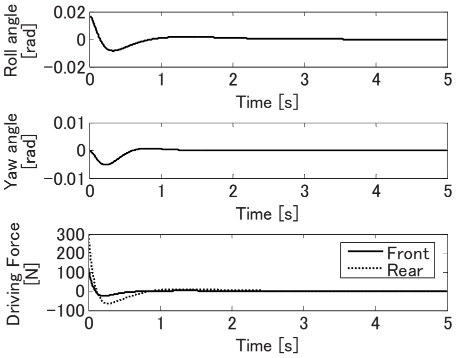

Fig. 9. Roll, yaw and driving forces at δ_f= 10 degrees and γ= 1/2.

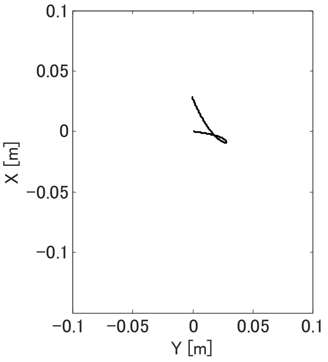

Fig. 10. Trajectory at δ_f= 10 degrees and γ= -1.

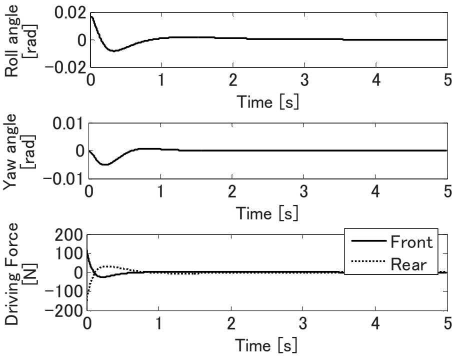

Fig. 11. Roll, yaw and driving forces at δ_f= 10 degrees and γ= -1.

At γ= -1/2 as shown in Fig. 12, the direction of the driving forces of the front and rear wheels are oppositely the same as at γ= -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.

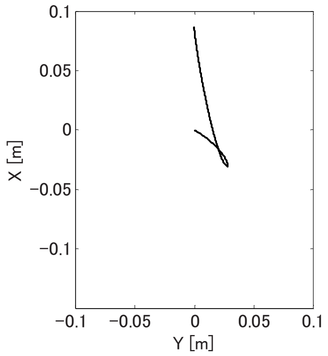

Fig. 12. Trajectory at δ_f= 10 degrees and γ= -1/2.

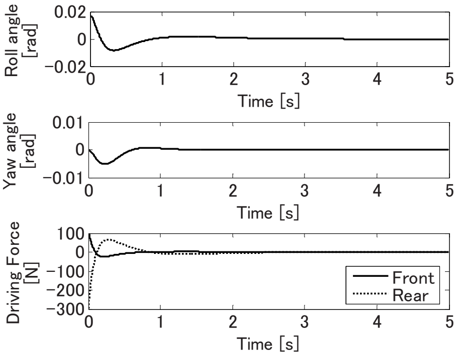

Fig. 13. Roll, yaw and driving forces at δ_f=10 degrees and γ=-1/2.

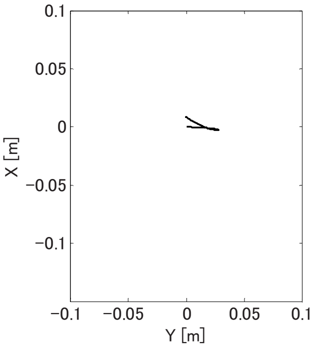

Fig. 14. Trajectory at δ_f= 30 degrees and γ= -1.

Next, the front steering angle is increased. Figs. 14 and 15 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. Fig. 16 is a plot of the maximum moving distance in the x direction

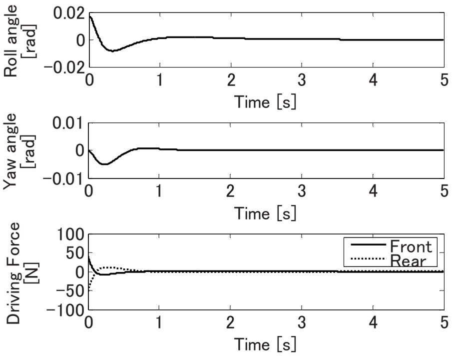

Fig. 15. Roll, yaw and driving forces at δ_f = 30 degrees and γ = -1.

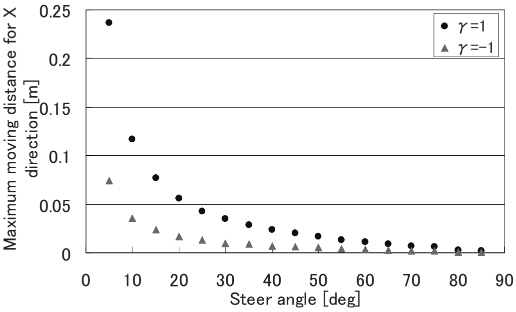

Fig. 16. Maximum moving distance.

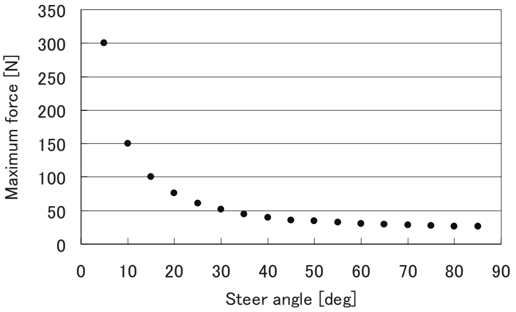

Fig. 17. Maximum driving force.

and Fig. 17 shows the maximum driving force. The maximum driving forces at $\gamma = 1$ 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 mode shown in Fig. 2. In this case, the equations of motion (1) to (4) correspond to the equations of an inverted pendulum.

5. Conclusion

We have proposed a concept of a novel PMV. We analyzed the stabilization method for a form of PMV that is a bicycle with two-wheel steering as well as two-wheel driving. The tendency of stability for such a bicycle with the control of driving forces was examined. We showed that the bicycle at low speed was stabilized at each steering angle. The effectiveness of our controller design was confirmed. We also found that a steering angle of more than around 30 degrees achieved stabilization control with small driving forces.

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