Development of a foldable personal mobility vehicle with one drive wheel

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Abstract. As a form of new transportation, cooperation of Personal Mobility Vehicles (PMVs) and a public transportation facility attracts attention from a viewpoint of an environmental load. Various compact PMVs adopting the attitude control technology of an inverted pendulum have been already developed. However, it is reported that attitude control becomes unstable under the influence of road surface irregular and level difference in the vehicle using this attitude control. Thus, a foldable three-wheel style PMV is developed in this research. By folding up, carrying into a public transportation facility called a railroad or a bus becomes easy. Moreover, static stability is sustained to the body by being grounded with a total of three wheels, two of which are used in front part whereas one is used in rear part. This needs no introduction of attitude control, which is to make the attitude stable under the influence of a road surface, so that the risk of a fall of a driver can be reduced. Furthermore, the number of sensors and the number of motors can be reduced by setting not to use attitude control and a drive wheel to one. Thereby, the manufacture cost of the body can be held down. Therefore, it is economical, so that it is thought that general spread is easy. This paper reports the outline and design of hardware to be developed, the running speed control technique, and some running performance experiments to be conducted.

1. Introduction

Cars are used as a means of transportation in various scenes. This progress of motorization involves problems of air pollution and global warming due to the increased emission of CO2 and NOx [1]. Therefore, as a new form of transportation, cooperation of personal mobility vehicles (PMVs) and public transportation facilities attracts attention from a viewpoint of the environmental load [2]. Parallel two-wheel type PMVs including Segway, adopting the attitude control technology of inverted pendulums [3], have been already developed. However, the attitude control is unstable due to the influence of road surface irregularities and level differences [4][5]. As the result, this type of PMV has a risk that the attitude control becomes unstable under irregularities in our living environment and the rider finally falls over.

Therefore, we develop a foldable three-wheel style PMV in this research. By folding the vehicle up, we can carry it into a public transportation facility such as a railroad or a bus. Therefore, it can be used not only for moving to stations or bus stops, but also for moving after getting off the railway or the bus. Furthermore, due to the fact that we can carry it into public transportation facilities, it is considered that such users contribute to decreasing of illegal parking around stations or bus stops. In addition, since this
PMV is grounded by three wheels, two of which are used in front part whereas one is used in rear part, this vehicle has static stability. Therefore, even if the attitude control is not well functioned, the rider can balance himself and maintain his posture. As a result, it need not adopt attitude control, and a risk of falling over due to road irregularities decreases. In this paper, we describe the overview of our PMV, its mechanical design, a revolution speed control method, and the running performance of a foldable PMV with one drive wheel. In addition, we report the result of an experiment evaluating our prototype vehicle.

2. Overview of PMV under development

Figure 1 shows a whole appearance of PMV under development. This PMV is foldable as shown in figure 2.

![Figure 1. Whole appearance of the prototype.](image)

![Figure 2. Running mode and folded mode.](image)

In the running mode, the machine size is 40 cm in width, 50 cm in maximum depth and 139 cm in maximum height. In the folded mode, the size is 40 cm in width, 33 cm in depth and 63 cm in height. Therefore, the depth is 34 % smaller, and the height is 55 % smaller than the running mode. In addition, since this PMV is grounded by three wheels, two of which are used in front part whereas one is used in rear part, this vehicle has static stability. Therefore, even if the attitude control is not well functioned, the rider can balance himself and maintain his posture. As a result, adopting attitude control is not necessarily needed, and a risk of falling over due to the irregularities decreases. Furthermore, a T-shaped handle and rotary steps are adopted to improve the performance of overcoming a level difference in roads. These parts allow us easily to use techniques such as wheelie and unweighting which are used when bicycles overcome level differences. By lifting the front follower wheels, it is possible to approach the differences with only the drive wheel. Moreover, by using an unweighting technique, the vehicle can overcome the level differences even if the driving motor is not so powerful. Acceleration and deceleration of the running speed are achieved by operating a throttle mounted on a handle bar. The maximum running speed is 6 km/h which is equivalent to the electric wheelchair common in terms of the vehicle assumed to be used on walkways. In addition, 6-inch air tires are adopted for all wheels. Since a skateboard track is adopted as the steering mechanism, the front wheels are steered by shifting the rider's weight to the left or right. The weight of the vehicle is 7.8 kg, and the maximum weight of the rider is 90 kg.
3. **Design of drive mechanism**

In this section, after giving the overview of a drive system, we examine the maximum revolution speed and torque of the drive wheel, and the performance of the encoder used for measuring the revolution speed.

3.1. **Overview of drive mechanism**

Figure 3 shows the overview of the drive mechanism.

![Figure 3. Overview of the drive part.](image)

A geared DC motor taken out from KYOCERA Industrial Tools Corporation's electric driver drill “BDM-180” is used as a driving motor. The maximum revolution speed is 2000 rpm and the maximum torque is 20 N\( \cdot \)m. The reduction ratio between bevel gears is 1, and the reduction ratio between roller chain sprockets is 3. Therefore, assuming that transmission efficiencies between the bevel gears and between the roller chain sprockets are 0.98 and 0.8 respectively, the maximum revolution speed of the drive wheel and the maximum torque become 666 rpm and 47 N\( \cdot \)m respectively. As the rotary encoder and the slit disk used for feeding back the revolution speed of the driving wheel, KODENSHI Corporation's “KE-203” and “KE-203 DISK” are adopted respectively.

3.2. **Examination about maximum revolution speed**

When the vehicle runs at 6 km/h which is the maximum speed, the drive wheel rotates at 212 rpm. As mentioned in subsection 3.1, the drive wheel in the vehicle can rotate at up to 666 rpm. Considering these facts, the drive mechanism has a margin of 68 % in a generatable revolution speed of the drive wheel. Therefore, it is said that the drive mechanism performance is sufficient.

3.3. **Examination about maximum output torque**

When the vehicle runs on a walkway, there are some scenes such as plane running, slope running, and overcoming a level difference between a roadway and a walkway. Since it is considered that plane running is also possible if slope running is possible, only the slope running and the overcoming level differences are examined in this paper. The total mass of summing a rider to the vehicle is 97.8 kg and the gravitational acceleration is assumed to be 9.8 m/s\(^2\). We ignore the moment of inertia of the wheels to ease the examinations in the following sections.
3.3.1. *In the case of slope running.* Figure 4 shows a schematic diagram when the vehicle is running on a slope.

![Figure 4. Case of running on slope.](image1)

In Japan, the maximum slope of walkways is stipulated as 8 % (4.57 deg) at the maximum according to “Standards related to the general structure of walkways” issued by the Ministry of Land, Infrastructure and Transport. Therefore, dividing the gravity working to the system into the direction parallel to the slope and the direction perpendicular to the slope, the former is reduced to 76.4 N whereas the latter is 955.4 N. Therefore, letting the rolling friction coefficient between the tire and a walkway be 0.005, the rolling frictional force of the tire is calculated as 4.8 N. Thus, in order to climb the slope, the propulsive force is required larger than 81.2 N, which is the sum of the frictional force and the force parallel to the slope. On the other hand, since the radius of wheel is 0.075 m and the maximum torque of the drive wheel is 47 N·m, the maximum propulsive force without slippage is 627 N. Therefore, assuming that the ratio between the loads on the front and rear wheels is given as 15:9, which is a ratio calculated by 3D-CAD “Inventor 2016”, the normal force from the slope in the rear wheel is 358.1 N. If the maximum static friction coefficient between the tire and the road surface is 0.8, the maximum static friction force is estimated as 286 N. Thus, the maximum propulsive force that can actually be output is 286 N and there is a margin of 72 % to climb a slope of the gradient 8 %.

3.3.2. *In the case of overcoming level differences.* Figure 5 shows a schematic view around the front wheels in the case of overcoming a level difference in a road. Let $F$ be the propulsive force, $W$ be the sum of loads acting on the two front wheels, $h$ be the height of a level difference, and $r$ be the radius of the wheels. The following equation is a requirement for that the front wheels, which are followers, overcome the level difference when the vehicle runs at a low speed.

$$|F| > \sqrt{h(2r-h)}|W|$$

(1)

Solving this equation for $h$, it yields that

$$h < r - \frac{|W|r}{\sqrt{|F|^2 + |W|^2}}$$

(2)
Like the case of slope running, assuming that a ratio of the loads on the front and rear wheels is given as 15:9, the front wheel receives a load of 599 N, whereas the rear wheel receives a load of 359 N. Letting the coefficient of static friction between wheels and a walkway surface be 0.8, the maximum static friction force is estimated to be 288 N. As described in the previous section, the maximum propulsion force of drive wheel is 627 N without the slippage, so that the maximum propulsion force that is actually able to output is 288 N. Therefore, assuming that $r = 0.075 \text{ m}$, $W = 599 \text{ N}$ and $F = 288 \text{ N}$, the height of a level difference $h$ that the vehicle can overcome is calculated as less than 0.0074 m. Most of level differences supposed to exist in Japanese walkways are the difference between walkways and roadways, and protrusions of braille blocks. Following “Standards related to the general structure of walkways” issued by the Ministry of Land, Infrastructure and Transport, the standard height difference between the walkways and roadways is defined to be 0.02 m. On the other hand, the protrusion height of braille blocks is defined to be 0.005 m in Japan Industrial Standards. Therefore, it is considered for the drive mechanism that it has a sufficient performance to overcome protrusions of braille blocks, but not enough for level differences between the walkways and roadways. To overcome the level differences, the rider needs to use techniques such as unweighting and wheelie.

3.4. Examination about the performance of encoder

The photo interrupter KE-203 has a response frequency of 20 kHz. In the case of running at 6 km/h, which is the maximum speed of the vehicle under development, the revolution speed on the axis to be measured is about 11 rps. Therefore, since the number of slits on the KE-203 DISK is 100, the response frequency of 1.1 kHz is required for the encoder. As described above, the KE-203 satisfies the required performance, so that the revolution speed is satisfactorily measured.

4. Revolution speed control for drive wheel

In this section, we explain about the revolution speed control for the drive wheel, the microcomputer for calculation, the motor driver, the control method, and the accelerator throttle.

4.1. Microcomputer for calculation and motor driver

Espressif Systems' microcomputer “ESP-WROOM-32” is adopted for performing the revolution speed control. In addition, Dimension Engineering's motor driver with a regenerative brake function “SyRen25” is adopted. The ESP-WROOM-32 sends a PWM signal as the operation input to the SyRen25.

The speed control period is set to 20.0 ms (50 Hz), and the period of the PWM is set to 2.0 ms (500 Hz). In the SyRen25, the output voltage is determined by the time length in which the PWM signal is high. The output voltage becomes the maximum in forward direction when the high level time is 2.0 ms, and it is 0 when the time is 1.5 ms. Therefore, the motor rotates in the maximum speed when the PWM duty ratio is 100 %, and stops when the ratio is 75 %. In addition, the resolution for the PWM signal in ESP-WROOM-32 is 12-bit.

4.2. Method to control revolution speed

The control system has two controllers: a PI controller and an open-loop controller. The system finally controls a motor by switching them. Figure 6 shows the switching of the controllers. First, a current revolution speed of the drive wheel measured by an encoder is compared with a target revolution speed, which is determined by the amount of inputs in the accelerator throttle. When the current speed is lower than the target value, in other words, when acceleration is required, the PI controller operates. On the other hand, when the current speed exceeds the target value, in other words, when deceleration is required, the open-loop controller operates. The speed control is executed every 0.02 ms.
4.2.1. **PI controller.** The PI control algorithm is shown in equation (3) and equation (4).

\[
\Delta u(n) = K_p\{e(n) - e(n-1)\} + K_i \cdot e(n) \tag{3}
\]

\[
u(n) = u(n-1) + \Delta u(n) \tag{4}
\]

Here, \(K_p\), \(K_i\) and \(e(n)\) denote a proportional gain, an integral gain, and an error deviation between the current measured speed value and the target value respectively. \(u(n)\) is the current manipulated variable expressed in the PWM duty ratio. \(\Delta u(n)\) represents the change amount of the manipulated variables. We empirically set the proportional gain and the integral gain to 0.30 and 0.075 respectively. Furthermore, in order to prevent a rider from breaking his balance due to sudden speed changes, \(\Delta u(n)\) is limited to be between \(-0.0375\%\) and \(0.0375\%\). For measuring the drive wheel revolution speed used as a feedback value, the encoder described in subsection 3.4 is used. The encoder pulses every the control cycle are measured by a counter in 4-multiplied. The maximum target value in revolution speed control is designed to be 212.2 rpm. When the drive wheel rotates at this revolution speed, the vehicle runs at 6 km/h in a case of that there is no slippage between the drive wheel and the road surface.

4.2.2. **Open-loop controller.** The open-loop control algorithm is shown in equation 5.

\[
u(n) = u(n-1) - C \tag{5}
\]

In equation (5), \(C\) denotes a constant duty ratio, whose value is 0.015 %. In the mechanism described in section 3, there is a case that the measurement speed increased rapidly due to an influence of backlash in the power transmission unit during deceleration. Due to this rapid change, the manipulated variable becomes excessively large if the feedback control is used during deceleration. This causes too large regenerative electric power. As a result, a protection circuit works and shuts down the SyRen25. The shutdown makes the vehicle stop suddenly, and the rider finally falls over. Therefore, influences due to this problem are decreased by using the open-loop control during deceleration.

4.3. **Accelerator throttle**

An overview of the accelerator throttle is shown in figure 7 and figure 8. The throttle consists of ABS resin frames, two tension coil springs, a neodymium magnet with the magnetic flux density of 280 mT, and two Hall sensors “A1324LUAT”. The rider controls the running speed by adjusting the amount of revolution in the throttle lever. Due to the extension coil springs, a restoring force always occurs against the lever. The revolution range of the lever is 50 deg, and the neodymium magnet rotates around the
same axis as the lever revolution. As a result, the magnetic flux density around the Hall sensors changes, and the output signals of the sensors change. Each Hall sensor is installed so that the relative angle is 50 deg around the same axis, and each output pin is connected to an I/O port of the ESP-WROOM-32. The voltage signal from each sensor is quantified by A-D conversion, and the amount of revolution in the throttle lever is measured based on the voltage. On the revolution of the lever, the voltage value from each sensor changes nonlinearly, whereas the difference in the signal values linearly changes. Therefore, a difference in A-D conversion values of the signals from each sensor is used to measure the amount of revolution. Then, as shown in figure 9, the target value of the revolution speed control is linearly determined from 0 to 212.2 rpm with respect to the amount of revolution in the throttle lever, where 0 to 5 deg is an idle range.

5. Experiment for evaluating control performance of running speed
In this section, we describe some experiments for evaluating the followability of running speed to the target speed, under the condition of using the drive mechanism explained in section 3 and the revolution speed control mentioned in section 4.

5.1. Experimental method
We used the control algorithm and the parameters described in subsection 4.2. In these experiments, the running speed of the vehicle is converted from the revolution speed of the drive wheel. Moreover, the target value of the running speed is converted from the target value of the revolution speed control. We conducted experiments for two cases: one is that nobody was boarded on the vehicle and the other is that an adult rider with a weight of 72 kg was boarded. The target value of running speed was increased by 0.02 km/h every control cycle for 6 s from the start of the experiment. As a result, the target value
reached 6 km/h at 6 s from the start. And then, the vehicle ran for 10 s with the same target value. The target value was changed to 4 km/h at the time when just 10 s has passed, and the vehicle finally ran at the same target speed for 15 s. After that, the target value was changed to 0 km/h for the vehicle to stop. The logging data was remotely recorded via a Bluetooth serial port.

5.2. Results and considerations of experiment

Figure 10 shows a transition of running speed in a case without loads, and figure 11 shows the transition in a case in which 72 kg weighted man was boarded.

![Figure 10. Running speed transition in no load case.](image1)

![Figure 11. Running speed transition in case of 72 kg man boarding.](image2)

It is confirmed that there is no significant delay in tracking the target values of the running speed between the both cases. Therefore, we can say that the followability of the vehicle is high. In addition, it was confirmed that the vehicle was able to gently stop without being affected by the backlash. However, since experiments were conducted for only two cases in this experiment, it needs to evaluate the influence due to load differences by conducting the same experiment by various riders with different weights.

6. Conclusion and future work

In this paper, we have proposed a foldable personal mobility vehicle with one drive wheel. In particular, we described the overview, the mechanical design, and the revolution speed control method, and moreover gave some results and considerations about the running experiment using the prototype.

As future work, we will perform improving a mechanical backlash, conducting the control performance evaluation of the running speed with different weight riders, measuring the minimum turning radius, and evaluating the performance to overcome level differences in roads.

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