Steering Control of the Personal Riding-type Wheeled Mobile Platform (PMP)

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Abstract – **This paper reports on the continued development of a new concept for a personal vehicle called the 'Personal riding-type wheeled Mobile Platform (PMP)' that consists of two wheels and a standing base for a human rider. The two wheels are driven independently, and forward and backward movement and steering are achieved by simply changing the relative position of the rider's center of gravity (COG) on the base. The vehicle has two distinct advantages: a reduction in total weight through its simple structure and a space-saving design that does not use a steering unit. We have already proposed the first prototype (PMP-1) and its posture stabilizing and running control methods, and we have achieved proper forward and backward movement according to the rider's intentions. This paper describes our proposed structure for detecting the rider's COG on the base and the steering control method in order to achieve steering control by changing the position of the rider's COG. and the second prototype (PMP-2) whose weight is smaller than 12kg. We also investigated the steering control method to improve maneuverability in various estimated standing poses. Our experimental results demonstrate that natural steering control can be achieved using the rider's COG based on the rider's intentions.**

Keywords: Inverted pendulum, Vehicle, Wheeled system, State feedback, Steering control, Personal mobile platform(PMP)

I. INTRODUCTION

Simple and lightweight vehicles are expected to emerge as personal ground transportation devices. The motorcycle, electric wheelchair, motor-powered bicycle, etc. have been developed and are useful for facilitating human transportation. However, such devices are neither small nor light, making it difficult to carry or store them in small spaces.

The Segway™ Human Transporter [1] was recently developed and it is on the market. It is a new type of personal vehicle that has only two coaxially mounted wheels and a steering bar, thereby occupying a small space. Its method of propulsion is a kind of wheeled inverted pendulum that can be balanced by the driving force of each of the two wheels to stabilize the whole system including the rider. Forward and backward movement is achieved by the rider's changing the position of his/her center of gravity (COG), and the vehicle is steered by rotating the throttle by hand. However, the total weight is approximately 38[kg], which is too heavy to carry by hand.

Fig. 1 Outdoor running experiment of personal riding-type wheeled mobile platform (PMP)

In our research we propose another type of a personal vehicle called the 'Personal riding-type wheeled Mobile Platform (PMP)' that consists only of two wheels and a standing base for the rider, as shown in Fig. 1. The two wheels are driven independently and the rider can travel and steer by changing the relative position of his/her COG relative to the base. The PMP has the following three main features:

1) Lightweight simple structure (Our target weight is under 12[kg]).
2) Space saving design without a steering bar.
3) Traveling control (running and steering control) using the rider's COG

To develop the PMP and bring it to market, the following basic problems must be solved first:

(1) Posture stabilization control while the rider is standing on the base

(2) Forward and backward running control using the movement of the rider's COG.

(3) Steering control using the movement of the rider's COG.

We have already introduced the first prototype of the 'Personal riding-type wheeled Mobile Platform' (PMP-1) and proposed the control method for its posture stabilization (1) and forward and backward running (2) [2]. The effectiveness of these control methods have been demonstrated in computer simulations and experiments with human riders.

In order to achieve proper steering control using the rider's COG (3), our sensing system for detecting the rider's COG on the base and the steering control methods are proposed in this paper. The sensing system is installed on the second prototype of the 'Personal riding-type wheeled Mobile Platform' (PMP-2) whose size is smaller than PMP-1 and weight is 11.8[kg]. We also investigated a steering control method to improve maneuverability depending on the estimated standing poses. Our experimental results demonstrate that the steering control can be properly achieved using the rider's COG based on the rider's intentions.

II. SECOND PROTOTYPE OF PMP (PMP-2) AND ITS SENSING SYSTEM OF THE RIDER'S COG

Figure 2 is a photo of PMP-2, which consists of a standing base for the rider and two wheels coaxially placed on both sides of the base. Contained inside the base are two DC servo motors (150[W]) with a rotary encoder and harmonic drive gear (reduction ratio: 1/50), two amplifiers for these motors, an accelerometer, a rate gyroscope, a board computer (Pentium 3, 233MHz), IO boards (AD/DA converters, counters and wireless LAN) and batteries. Either of the DC servo motor drives each wheel, and the rotation of the wheel is detected by the rotary encoder. The accelerometer and the rate gyroscope respectively detect the inclination angle and the angular velocity of the base in the pitch direction. RT-Linux is used for the computer's operating system to achieve fast servo cycles, and the total weight of PMP-2 is 11.8 [kg].

In order to detect the position of the rider's COG on the standing base, the sensing system is designed as shown in Fig. 3. The sensing system consists of the rider's standing plate attached to the central frame of the body and four force plates with strain gauges, which are attached to the right-front, the left -front, the right-rear and the left-rear of the central frame respectively, in contact with the standing plate. Although the shape of the plate is deformed by the changing of the 2-dimensional position of the rider's COG while he/she is on the standing base, the position of the rider's COG can be estimated using the four force sensor's outputs as described later by Eq. (3) and (6).

Fig. 2 Second prototype (PMP-2) of personal riding-type wheeled mobile platform

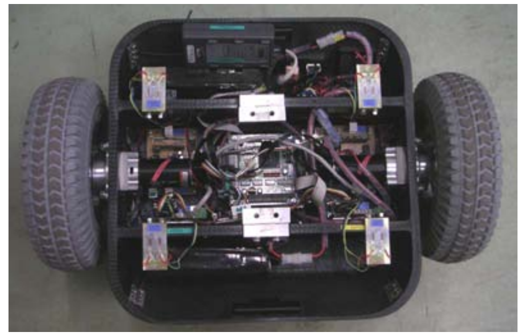
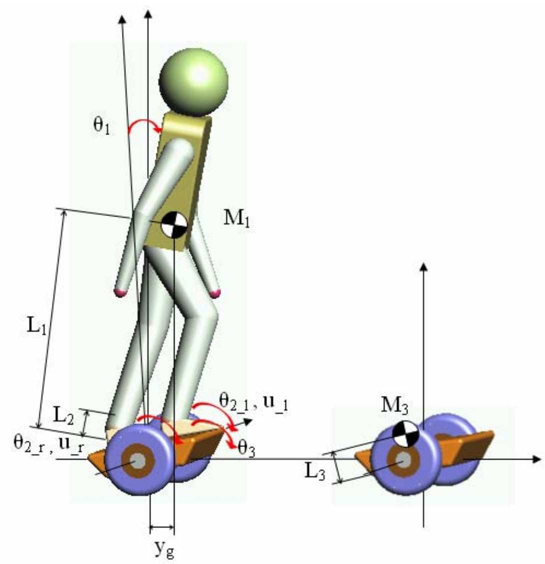


Fig. 3 PMP sensing system of the rider's COG

III. RUNNING AND STEERING CONTROL METHOD OF PMP-2 WITH A HUMAN RIDER

PMP-2 with a standing human rider, as illustrated in Fig. 1, is considered to be a kind of wheeled inverted pendulum. It is a statically unstable system in the pitch direction and stable in the roll direction, because only two wheels are in contact with the ground (as detailed in Fig. 4). To stabilize the whole system in the pitch direction, we assume the rider to be a rigid body with only one joint at the rider's ankle.



θ_1: Relative inclination angle of human relative to the base
θ_{2_r}, θ_{2_l}: Rotation angle of the right and left wheels
θ_3: Inclination angle of the base
M_1, M_3: Mass of human and base
L_1: Length between the center of the ankle joint and the COG of human
L_2: Length between the wheel axle and the center of the ankle joint
L_3: Length between the wheel axle and COG of the base
$u_{\_r}$, $u_{\_l}$: Motor current of right and left wheel
y_g: Position of COG of rider in y coordinate

Fig. 4 Parameters of PMP-2 with a rider

To stabilize the posture of PMP-2 including a rider in the pitch direction, we adopted the following state feedback control method for the wheeled inverted pendulum [2][3] as shown in Eq. (1). This is because θ_3 and $\dot{\theta}_3$ are detected by the combination of an accelerometer and a rate gyroscope, and

θ_{2_r} , θ_{2_l} , $\dot{\theta}_{2\_r}$ and $\dot{\theta}_{2\_l}$ are detected by the rotary encoders attached to the right and left motors and their numerical differentiations, respectively. All state variables could be detected using sensors if we assume the rider is rigidly fixed on the PMP-2 base, that is θ_1 is constant. Strictly speaking, the rider is not rigidly fixed on the base, which makes it difficult to determine the exact state feedback gains by setting the desired poles of the system. With this assumption, we calculated the above state feedback gains, k_1-k_4, using the pole assignment method. By changing the values of $\dot{\theta}_{ref\_r}$ and $\dot{\theta}_{ref\_l}$ shown in Eq. (2), the system could be moved forward and backward, and be steered. For forward and backward running using human inclination relative to the base in the pitch direction, we set the inclination angle of the base θ_3 proportional to human inclination θ_1 as acceleration reference of the movement [2]. For the steering movement, we set the difference between the sum of the two right force sensors outputs and the two left force sensors outputs as differential reference of angular velocities of the right and left wheels.

$$\begin{aligned} u_{\_r} &= k_1\theta_3 + k_2\left(\theta_{2\_r} - \int \dot{\theta}_{ref\_r}\right) + k\dot{\theta}_3 + k_4\left(\dot{\theta}_{2\_r} - \dot{\theta}_{ref\_r}\right) \\ u_{\_l} &= k_1\theta_3 + k_2\left(\theta_{2\_l} - \int \dot{\theta}_{ref\_l}\right) + k\dot{\theta}_3 + k_4\left(\dot{\theta}_{2\_l} - \dot{\theta}_{ref\_l}\right) \end{aligned} \tag{1}$$

where,

$$\begin{aligned} \dot{\theta}_{ref\_r} &= -\int k_a\theta_3 + k_b\{(F_{rf} + F_{rr}) - (F_{lf} + F_{lr})\} \\ \dot{\theta}_{ref\_l} &= -\int k_a\theta_3 - k_b\{(F_{rf} + F_{rr}) - (F_{lf} + F_{lr})\} \end{aligned} \tag{2}$$

$\dot{\theta}_{ref\_r}, \dot{\theta}_{ref\_l}$: Reference rotational angular velocity of the right and left wheels

k_1-k_4: State feedback gains for stabilization

k_a: Gain for reference acceleration for forward and backward movement

k_b: Gain for reference velocity for steering movement

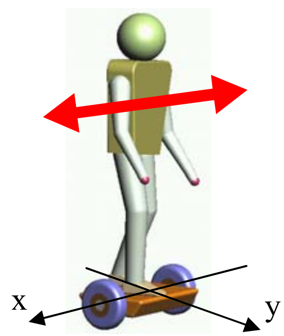
F_{rf}, F_{rr}: Sensor output of the right front and right rear force plates

F_{lf}, F_{lr}: Sensor output of the left front and left rear force plates

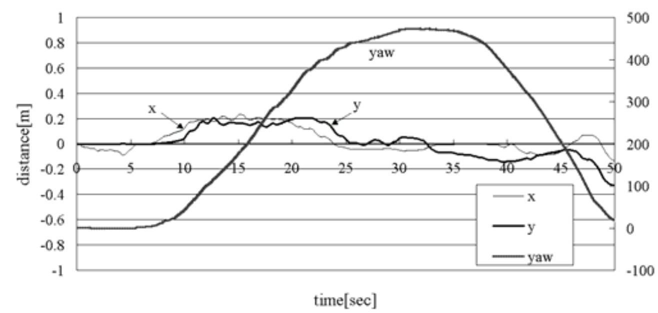
IV. EXPERIMENT ON STEERING CONTROL OF PMP-2

A. Steering movement control while keeping the constant position

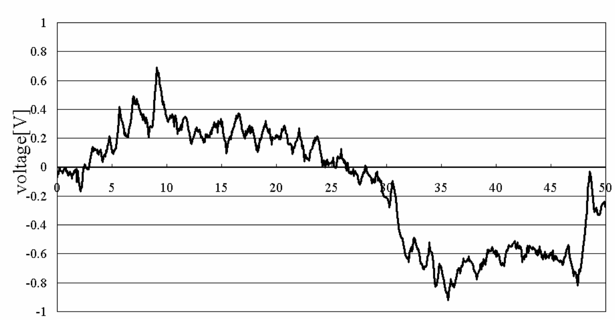
To confirm the effectiveness of our proposed steering control method, we performed rotation movement experiments in the yaw direction while keeping the constant position. In the experiment results shown in Fig. 5, a human rode on the PMP-2 placing his right foot in a forward position and left foot in a backward position relative to the axle of the wheels (shown in Fig. 5 (i)) to increase the stiffness of the whole system, including the human rider, in the pitch direction. By moving the COG of the rider straight on the axle between the right and left wheels according to his/her intention, rotation movement in the yaw direction while keeping the constant position was achieved. Figure 5 (ii) and (iii) shows the experimental results of this rotation movement. In the experiment, the rider first moved his/her COG toward the right wheel along the axle of both wheels and, as a result, the PMP-2 rotates clockwise in the yaw direction. Next the rider moved his/her COG toward the left wheel along the axle of both wheels and, as a result, the PMP-2 rotated counter-clockwise in the yaw direction. Figure 5 (ii) shows the x-y position difference within 0.2 [m] and more than 1 rotation in yaw direction. This result means that rotation movement was achieved in the yaw direction approximately while keeping the constant position. Figure 5 (iii) shows that the sum of the right force sensor outputs exceeds the sum of left force sensor outputs in the clockwise yaw movement. On the other hand, in the counter-clockwise yaw movement, the sum of left force sensor outputs exceeds the sum of right force sensor outputs. This result demonstrates that our proposed steering control method shown in Eq. (1) and (2) works well.



(i) Standing pose of the rider and moving direction of COG



(ii) x-y distance and yaw angle

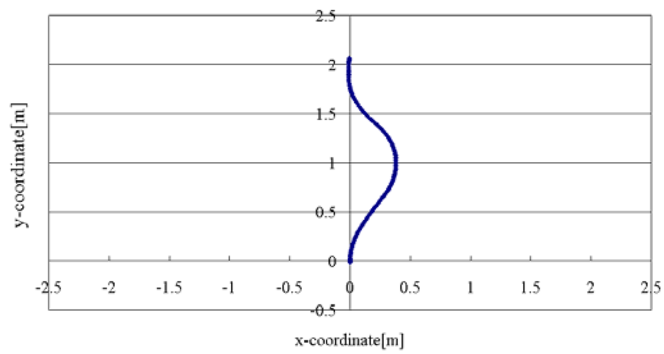


(iii) Difference between the sum of the right and left force sensor outputs

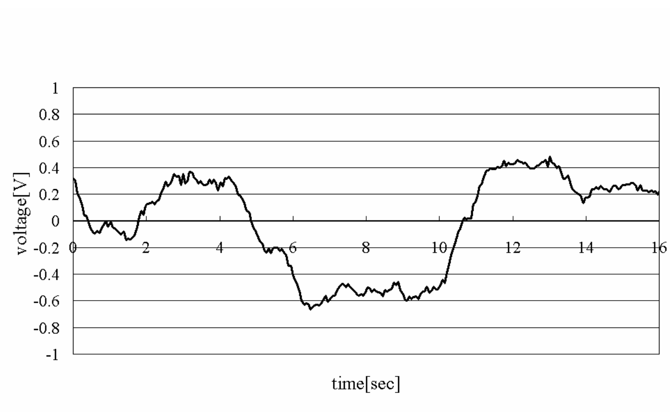
Fig. 5 Experimental results of rotation movement in yaw direction while keeping the constant position

B. Steering Movement Control while going forward

Figure 6 shows the experimental results of steering movement with forward and backward movement control. In the experiment, the human rode on the PMP-2 with same foot position as shown in Fig. 5 (i). First, the rider moved his/her COG toward the right-front direction on the base to achieve right-forward steering movement of the PMP-2. Next, the rider moved his/her COG toward the left-front direction to achieve left-forward steering movement of the PMP-2. Finally, the rider moved his/her COG toward the right-front direction again, and then stopped. As a result, the PMP-2 moved along the path shown in Fig. 6 (i). This result demonstrates that the right and left steering control can be properly achieved according to the rider's intention. Figure 6 (ii) shows the force sensor outputs. These are the same outputs according to the rider's COG as described in the previous section. However, the moving velocity of the right-forward steering exceeds the velocity of the left-forward steering, because the human rode on the PMP-2 placing the right foot in a forward position and the left foot in a backward position relative to the axle of the wheels (shown in Fig. 5 (i)).



(i) Moving path of the base



(ii) Difference between the sum of the right and left force sensor outputs

Fig.6 Experimental results of steering motion control

V. IMPROVEMENT OF STEERING MANEUVERABILITY USING THE RIDER'S ESTIMATED STANDING POSES

A. Estimation of the rider's standing poses using force sensor outputs

As mentioned above, the rider can ride on the PMP-2 standing in various poses, e.g. placing the right foot in a forward position and the left foot in a backward position relative to the axle of the wheels (shown in Fig. 7 (i)), placing both feet just above the axle of the wheels (shown in Fig. 7 (ii)), placing the left foot in a forward position and the right foot in a backward position relative to the axle of the wheels (shown in Fig. 7 (iii)). This makes it difficult to perform running and steering control according to the rider's intention using the proposed method shown in Eq.(1) and (2). Therefore, to investigate the possibility of estimating the rider's standing poses, we performed basic experiments to monitor the four force sensors under various standing poses. Figure 7 shows the experimental results when the rider changed the standing pose slowly from (i) to (iii) during stable control of the PMP-2. The solid line shows F_{sa}, the sum of the right-front (F_{rf}) and left-rear (F_{lr}) force sensor outputs, and the dashed line shows F_{sb}, the sum of the left-front (F_{lf}) and right-rear (F_{rr}) force sensor outputs. In standing pose (i), F_{sa} is larger than F_{sb}. In standing pose (ii), F_{sa} is approximately equal to F_{sb}. In standing pose (iii), F_{sa} is smaller than F_{sb}. This result demonstrates that estimation of standing pose is possible using the relationship between F_{sa} and F_{sb}.

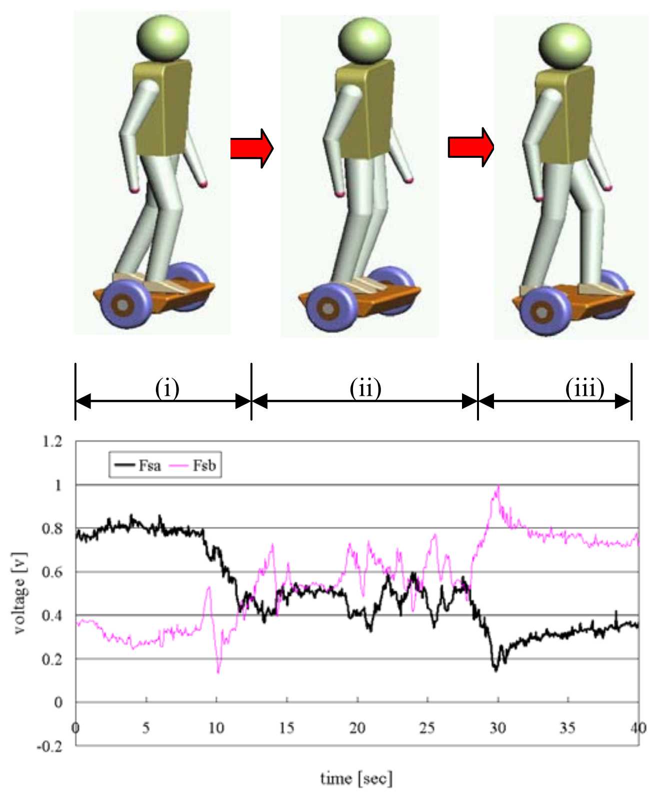


Fig. 7 Experimental results of rider's changing standing poses during stable control of PMP-2

B. Compensation method of running and steering control depending on three standing poses

To improve the maneuverability of the steering control, we propose a compensation method depending on the three standing poses. First, we can estimate the position in the x coordinate of the rider's COG shown in Fig. 8 using the force sensor outputs as shown in Eq. (3).

$$x_g = k_x\{(F_{rf}+F_{rr})-(F_{lf}+F_{lr})\} \tag{3}$$

On the other hand, the position in the y coordinate of the rider's COG as shown in Fig. 8 can be estimated using the following two equations.

$$(M_1 l_2 + M_3 l_3)\sin\theta_3 + M_1 l_1 \sin(\theta_1+\theta_3) = 0 \tag{4}$$

$$y_g = L_1 \sin\theta_1 \tag{5}$$

Equation (4) shows the relationship between θ_1 and θ_3 at the constant state (when running velocity and acceleration are zero) during the stable control of PMP-2[2]. Equation (5) shows the relationship between the position in the y coordinate of the rider's COG and the inclination angle of the rider in the pitch direction as shown in Fig. 4. By linearizing Eq. (4) and (5), because θ_1 and θ_3 are close to zero, the following equation is derived. Using Eq. (6), the position in the y coordinate of the rider's COG can be estimated.

$$y_g = \frac{-(M_1 l_1 + M_1 l_2 + M_3 l_3)}{M_1}\theta_3 \tag{6}$$

As a result of the above consideration, using the force sensor outputs, the foot position on the base can be estimated during stable control. Therefore, we can obtain k_g, the inclination of the line connecting the right and left foot position as shown in Fig. 8.By using the following two equations, we obtain the compensated acceleration reference α_{ref} shown in Fig. 9.

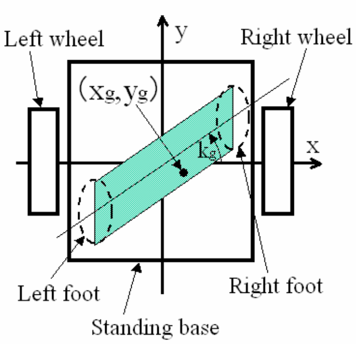


Fig.8 Position of both feet and the rider's C.O.G

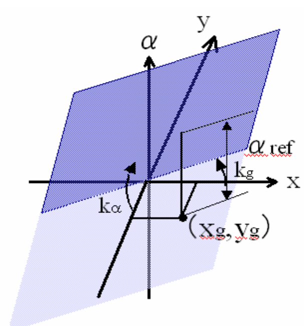


Fig.9 Relationships of α_{ref}, x_g and y_g

$$y_\alpha = k_g x_g - y_g \tag{7}$$

$$\alpha_{ref} = k_\alpha y_\alpha \tag{8}$$

We can achieve running and steering control relative to three standing poses by calculating the reference angular velocities for both wheels as shown in Eq.(9).

$$\begin{aligned}\dot{\theta}_{ref\_r} &= -\int \alpha_{ref} + k_b\{(F_{rf}+F_{rr})-(F_{lf}+F_{lr})\}\\ \dot{\theta}_{ref\_l} &= -\int \alpha_{ref} - k_b\{(F_{rf}+F_{rr})-(F_{lf}+F_{lr})\}\end{aligned} \tag{9}$$

C. Experiments on Steering Control

To investigate and compare our proposed running and steering control methods, we performed the following experiments based on the rider's standing posture shown in Fig.7 (i). Figure 10 shows the reference movement of right-forward steering and left-forward steering. Figures 11 and 12 show our experimental results for left-forward steering using the reference angular velocities of both wheels as shown in Eq. (2) (method (1)) and Eq. (9) (method (2)), respectively.

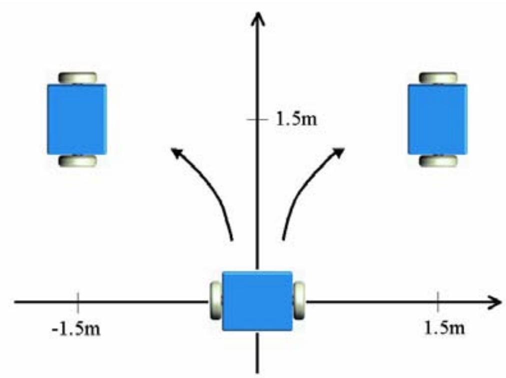


Fig.10 Reference paths of right-forward steering and left-forward steering movement

Concerning the position of the rider's COG in the x coordinate of the base, Fig. 11 (method (1)) shows the rider first moving his/her COG toward each wheel, then returning to the neutral position next, and then moving again. On the other hand, Fig. 12 (method (2)) shows the rider moving his/her COG smoothly. This means that, in method (1), the forward running velocity is easily decelerated in left-forward steering (as shown in Fig. 11). This is because the rider places the right foot in a forward position and the left foot in a backward position relative to the axle of the wheels. Concerning the posture of the base, Fig. 11 shows that the inclination angle that makes the running acceleration equal to zero is approximately equal to zero constantly. On the other hand, Fig. 12 shows that the above angle varies depending on the rider's COG in the x coordinate of the base. In method (2) our experimental results show that the traveling movements are very smooth in the x-y position and yaw angles of the PMP-2. The above results show that, from the viewpoint of steering maneuverability by the rider, steering control method (2) is preferable to steering control method (1).

VI. Conclusion

In this paper, we reported on a second prototype (PMP-2) of personal vehicle called the 'Personal riding-type wheeled Mobile Platform (PMP)' with a force sensing system to detect the position of the rider's COG, and proposed a steering control method using force sensor outputs. We first introduced the PMP-2 whose weight is under 12[kg] with the force

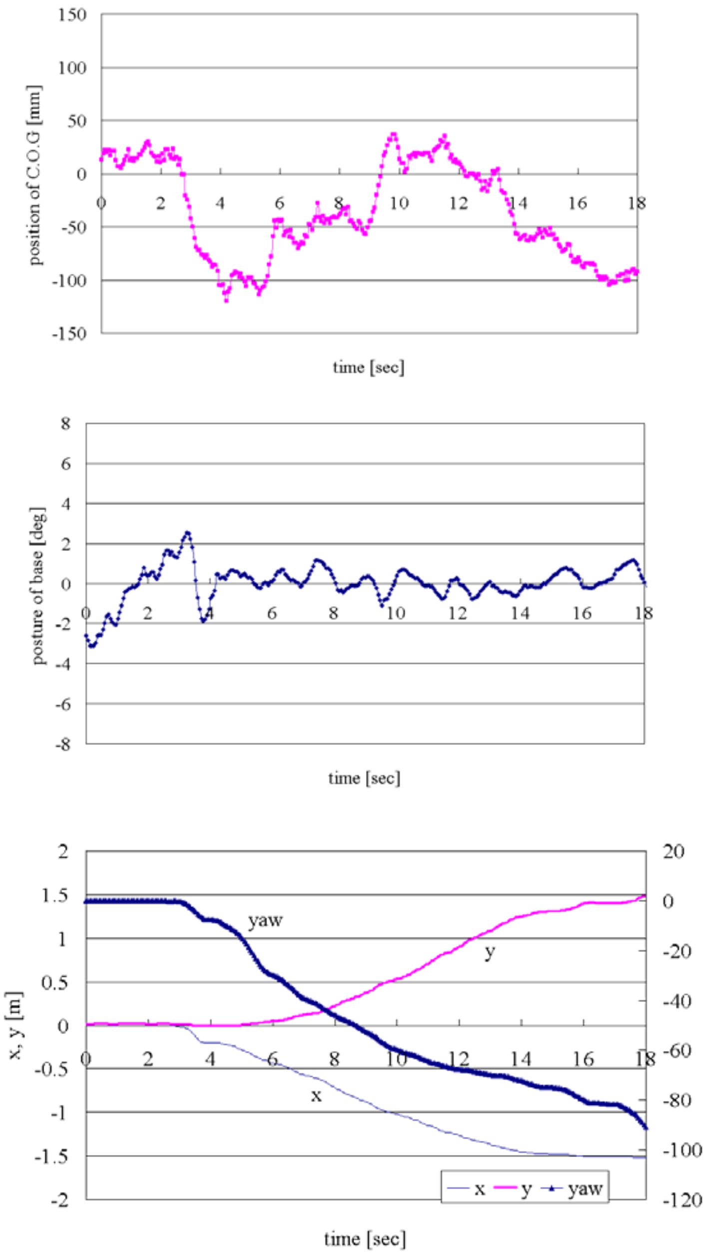


Fig. 11 Experimental results of left-forward steering (method (1))

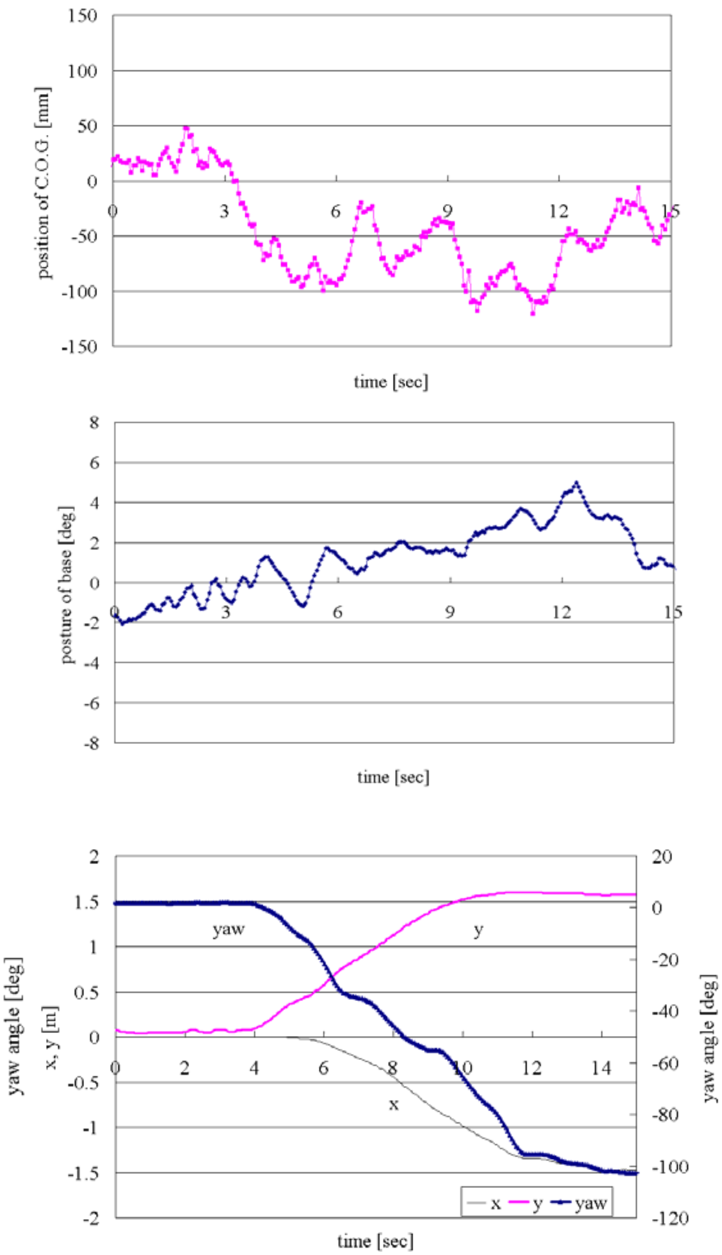


Fig. 12 Experimental results of left-forward steering (method (2))

sensing system and our basic steering control method using force sensors without considering the standing poses of the rider on the base. This method achieved proper steering movement control; however it made the rider feel the difference of acceleration in the steering movements of the right and left directions. Therefore, we proposed a compensation method for steering control considering the rider's standing poses. Our experimental results demonstrate that the steering maneuverability of the rider was improved using the steering control method with compensation. As a result, the effectiveness of our newly proposed sensing system for the position of the rider's COG and the steering control method of the refined PMP-2 was successfully demonstrated experimentally.

With this new model we plan to improve the running and steering maneuverability through experiments with many various riders in the very near future.

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