Development of a Personal Mobility Vehicle for Short-range Transportation Support

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Abstract—Short-range transportation vehicle is paid attention today. It is to use for commuting, delivery and so on. We have developed a Personal Mobility Vehicle for short-range transportation. This three-wheeled vehicle (two in front and one in rear) is propelled by kicking off the ground. To evaluate the personal mobility motion, drivability and stability, 6 DOF simulation model is proposed. In this paper, mathematical model of our developed personal mobility vehicle is presented. The model includes wheel model, suspension model and dynamical equation of motion of the body. And also, simulation results were compared with experimental results.

Keywords— personal mobility vehicle; three-wheeled; dynamics;

I. INTRODUCTION

Short-range transportation vehicle, personal mobility vehicle (PMV), is paid attention to use for commuting, delivery and so on. It is the one of the application of technology for saving energy and environment friendly to the sustainable future society. Motor companies have developed the short-range transportation vehicles for personal use, e.g. i-ROAD by Toyota Motor Co. [1], MC-β by Honda Motor Co., "New Mobility Concept" by Nissan Motor Co.. i-ROAD is a three-wheeled electrical powered compact vehicle. It is combined cars and motorbikes to solve the space problems of crowded traffic and parking. Segway [2] and Winglet are another types of PMV. It has two electrically driven wheels that placed in parallel. The user stands up on the vehicle and they can control the vehicle by shifting her/his center of gravity. Inverted pendulum control theory applied controller takes the balance of the vehicle. Honda Motor Company developed UNI-CAB [4] that is a robotic transporter. The user sits on the seat and controls the vehicle by changing her/his posture.

To extend the area of activity, we propose a new portable PMV. Our proposed PMV is three wheels (two in front, one in rear) layout. It is enabled to stand by itself and ensure a stable running. Diameter of the wheels is 200mm in order to get over the road gap. Maximum velocity is up to 6 km/h, according to the maximum velocity for a motor wheel chair. To bring it on to the public transportation, lightweight body and folding mechanism are equipped. PMV is propelled by kicking off the ground and power-assisted by the motor on the rear wheel. Power assist system consists of a servomotor, a rotary encoder, a micro controller and a motor driver. Rotary encoder is attached on the rear wheel and measures the wheel rotation. If angular acceleration of the rear wheel excess the threshold, micro controller estimates that the user kicked off the ground. Therefore, the servomotor starts to rotate and assist the rotation of the rear wheel to reduce the deceleration. Sifting drivers posture and the center of gravity to control the vehicle is challenging technologically however, from the viewpoint of safety and carrying some luggage or supplies, it is not advisable. Therefore, bar handle is used to control the vehicle.

II. PERSONAL MOBILITY VEHICLE

Our developed PMV is three wheels (two in front, one in rear) layout. It is enabled to stand by itself and ensure a stable running. Diameter of the wheels is 200mm in order to get over the road gap. Maximum velocity is up to 6 km/h, according to the maximum velocity for a motor wheel chair. To bring it on to the public transportation, lightweight body and folding mechanism are equipped. PMV is propelled by kicking off the ground and power-assisted by the motor on the rear wheel. Power assist system consists of a servomotor, a rotary encoder, a micro controller and a motor driver. Rotary encoder is attached on the rear wheel and measures the wheel rotation. If angular acceleration of the rear wheel excess the threshold, micro controller estimates that the user kicked off the ground. Therefore, the servomotor starts to rotate and assist the rotation of the rear wheel to reduce the deceleration. Sifting drivers posture and the center of gravity to control the vehicle is challenging technologically however, from the viewpoint of safety and carrying some luggage or supplies, it is not advisable. Therefore, bar handle is used to control the vehicle.
III. THEORETICAL MODEL OF PMV

Several previous studies of dynamics of three-wheeled vehicle, small automobile type, were confirmed [4,5,6,7]. In this paper, we propose a mathematical model of portable three-wheeled vehicle based on automobile dynamics model. The layouts of wheels are two in front and one in rear. Each wheel has suspension and damper element. Euler equations are integrated in this model.

A. Coordinate System

The motion of PMV is described in an inertial XYZ coordination system that is fixed on the ground. PMV body is introduced xyz coordinate system. The origin of coordinate system is attached on the center of the mass of PMV. Velocities of the PMV body \( u \), \( v \) and \( w \) are along to \( x \), \( y \) and \( z \) axis as well as its rotational velocity around axes are \( p \), \( q \) and \( r \).

Euler angles are used to describe the orientation of the PMV body.

B. Forces

Force is based on Newton’s equation for rigid body.

\[
F = ma
\]  

(1)

Where \( F \) is to accelerate the center of mass. External forces on each axis are as follows,

\[
\begin{bmatrix}
F_x \\
F_y \\
F_z
\end{bmatrix} = 
\begin{bmatrix}
\dot{u} + qw - rv \\
\dot{v} + ru - pw \\
\dot{w} + pv - qu
\end{bmatrix} \tag{2}
\]

These forces are transformed to inertial axis.

Longitudinal and lateral friction forces \( F_x \), \( F_y \) on the wheel contact point are calculated by friction coefficient \( \mu_x \), \( \mu_y \) and normal force \( F_n \)

\[
F_x = \mu_x F_n
\]

\[
F_y = \mu_y F_n
\]  

(3)

Normal force on each wheel is based on the spring force \( F_s \) and the damping force \( F_d \). Spring force is calculated by deflection of the suspension length and spring constant. Damping force is calculated by suspension stroke speed and damping constant.

\[
F_n = F_s + F_d
\]  

(4)

Friction coefficients on the ground contact point of each wheels \( \mu_x, \mu_y \) are calculated based on a magic formula [8]. Arguments of functions are wheel slip ratio \( s \) and wheel sideslip angle \( \beta \) of each wheel.

\[
\begin{align*}
\mu_x & = f_x(s,\beta) \\
\mu_y & = f_y(s,\beta)
\end{align*}
\]  

(5)

C. Moments

Moments of PMV body are calculated based on angular acceleration and angular velocity of the body coordinate system and also moment of inertia \( I_{xx}, I_{yy}, I_{zz} \). PMV moves up to 6 km/h and no high-speed motion e.g. quick turn. Therefore, product of inertia is omitted in this case.

\[
\begin{align*}
M_x & = \dot{p}I_{xx} - (I_{yy} - I_{zz})qr \\
M_y & = \dot{q}I_{yy} - (I_{zz} - I_{xx})pr \\
M_z & = \dot{r}I_{zz} - (I_{xx} - I_{yy})pq
\end{align*}
\]  

(6)

IV. SIMULATION RESULTS

Preliminary experiments of PMV were carried out to test the basic function. Two young participants (age 24 female and male), three elderly participants (age 60 female and age 72 male) were enrolled in the experiments. Experiments were done on indoor flat floor. Participants kicked off the ground only once as much as they can and held steering to move straight.

Fig. 3 shows the comparison of the results of velocity between simulation result (solid line) and experimental result (dashed line). In the experiment, participant was elderly male. On the simulation, propulsion force by kicking off the ground was provided as a longitudinal external force \( F_x \) on the center of gravity. Propulsion force was estimated according to the level of acceleration and acceleration time in the experiment. It was provided constantly 0.8 sec on the simulation. After accelerating, the velocity of PMV was reduced according to rolling resistance.

The maximum gliding velocity on the simulation was 1.198 m/s and 1.1931 m/s in the experiment. It is confirmed
that the similarity of velocity profile in accelerating and decelerating.

Fig. 4 shows the comparison of the results of gliding distance between simulation result (solid line) and experimental result (dashed line). The gliding distance was 2.17 m in the simulation and 2.23 m in the experiment. Distance in the experiment was calculated according to the velocity data. Before kicking off the ground, small movement was confirmed. And also, from 1.5 sec to 3 sec, velocity in the experiment is higher than simulation. It will be a cause of difference on the distance.

V. DISCUSSIONS

It is confirmed that simulation result and experimental result is approximately same in the case of acceleration and deceleration. The simulation model was validated.

Further more experiment including lateral motion will be held and evaluated in the next step. And also, mathematical model of propulsion assistance system will be integrated and tested.

VI. CONCLUSIONS

Three-wheeled vehicle 6 DOF simulation model is proposed in this paper. Mathematical model of our developed personal mobility vehicle is presented and compared simulation result and experimental result. As a result, the similarities of the results were confirmed.

REFERENCES

[1] TOYOTA (i-ROAD), http://www.toyota-global.com/innovation/personal_mobility/i-road/