

An Assist Control using an Electric Motor for One-wheel cart

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Abstract-- In recent years, the number of farmers in Japan has been declining and the population is aging. The electrification of the agricultural machines is one of solutions to reduce the work load of elder workers. However, electric powered one-wheel carts in current market on the market have the problem that they require accelerator operation. In order to solve this problem, this paper proposes an assist control for electric powered one-wheel cart implemented with inertia simulator. An inertia simulator can give the motor torque assist which achieves equivalently the no load condition for the operator. The proposed system was verified by simulation and the prototype one-wheel cart was designed.

Index Terms-- Disturbance Observer, Inertia Simulator, one-wheel drive

I. INTRODUCTION

According to statistics published by Japan's Ministry of Agriculture, Forestry and Fisheries, 40% of agricultural employees will be 65 years of age or older and 38% will be 75 years of age or older by 1991. Fig.1 shows the population of agricultural workers in Japan.

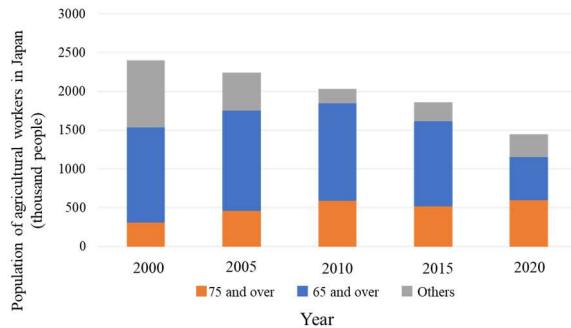


Fig.1 population of agricultural workers in Japan⁽¹⁾ This trend indicates that the number of employees is aging. The overall population of agricultural workers is also on a declining trend. Therefore, it can be assumed that the elderly have to handle heavy agricultural machinery, which is a burden on them. To address this problem, this study aims to reduce the burden on elderly farmers by converting one-wheel carts, which are widely used in agriculture, into electric-powered one-wheel carts. A one-wheel carts assisted by a motor already exists^{(2) (3)}. One problem, however, is that the need to control the speed of the one-wheel carts makes its handling as an agricultural machine complicated. In order to solve this problem, an inertia simulator is applied to the one-wheel cart control to eliminate the need for operation. An inertia simulator is a control method that simulates inertia by generating inertia

with torque output from a motor⁽⁴⁾. This control method is applied to assist control so that the apparent weight of the one-wheel cart becomes lighter even when the one-wheel cart is loaded with freight.

II. A ONE-WHEEL DRIVE MODEL

A one-wheel drive model is shown in Fig.2, and a parameter table is shown in Table 1.

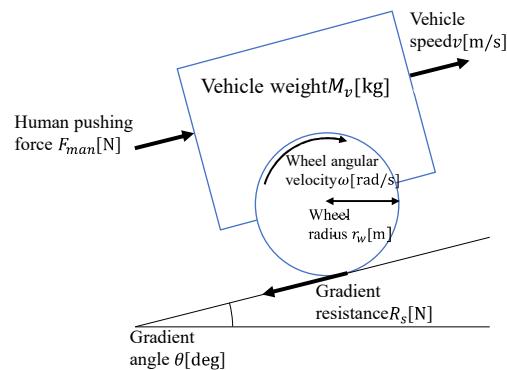


Fig.2 One-wheel drive model

TABLE I
TIMES NEW ROMAN TYPE SIZES AND STYLES

Symbol	Description	Value	Unit
M_v	Vehicle weight	7.365	[kg]
M_F	Freight weight	-	[kg]
r_w	Wheel radius	0.178	[rad/s]
J_w	Wheel inertia	0.0361	[kg·m ²]
B_w	Coefficient of Viscous friction	0.05	[kg·m/s]
g	Gravity acceleration	9.81	[m/s ²]
K_t	Motor torque constant	1	-
ω_c	Cutoff frequency	100	-
P_J	Proportional gain	20	-
ω	Wheel angular velocity	-	[rad/s]
v	Vehicle speed		[m/s]
$\hat{\omega}$	Generated wheel angular velocity	-	[rad/s]
T_e	Motor torque	-	[Nm]
I	Motor current	-	[A]
\hat{T}_d	Estimated disturbance	-	[Nm]
F_{man}	Human pushing force	-	[Nm]
\hat{F}_{man}	Estimated Human pushing force	-	[N]
θ	Gradient angle	-	[deg]
R_s	Gradient resistance	-	[N]

A. Modeling of a one-wheel cart

A one-wheel cart is considered as a single-wheel drive model for simulation in an inertial simulator and experiments. In this model, the contact between the wheel and the road surface does not have slip. The kinematic equation for the vehicle is shown in (1), and the kinematic equation for the wheel is shown in (2).

$$(M_v + M_F) \frac{dv}{dt} = F_{man} - R_s \quad (1)$$

$$J_w \frac{d\omega}{dt} = T_e - F_{man}r_w - B_w\omega \quad (2)$$

The relationship between wheel angular velocity and vehicle speed is shown in (3).

$$v = r_w\omega \quad (3)$$

From (1)~(3), the kinematic equations can be combined as wheel kinematic equation (4).

$$\begin{aligned} (J_w + (M_v + M_F) \cdot r_w^2) \frac{d\omega}{dt} + B_w\omega = \\ T_e - R_s r_w \end{aligned} \quad (4)$$

Finally, the wheel kinematic equation is described in (5).

$$\omega = \frac{1}{(J_w + (M_v + M_F)r_w^2)s + B_w}(T_e - R_s r_w) \quad (5)$$

B. The inertia simulator

The concept of this research is the motor torque assist control without any speed or accelerator operation. To achieve this concept, the inertia simulator is used to control the wheel speed as unload condition of the one-wheel cart by an estimation of human pushing force and a virtual model of one-wheel drive model.

To estimate the human pushing force, a disturbance observer is applied. Then, the inertia simulator calculates the wheel angular velocity using the virtual model of one-wheel drive model in unload condition. A disturbance observer is a control method that estimates disturbances using the inverse system of the plant.

In the inertial simulator, the plant is a single-wheel drive model, the input is the motor torque T_e , and the output is

the wheel angular velocity ω . The disturbance observer is shown in (6).

$$\hat{T}_d = (J_w + (M_v + M_F) \cdot r_w^2)s - B_w\omega - T_e \quad (6)$$

In addition, the inverse system of the model includes a differential term, there is a problem that the value of the estimated disturbance can vary greatly due to noise in the input. Therefore, a low-pass filter is installed at the output to remove the effect of noise.

C. Compensation of gradient resistance

The estimated disturbance \hat{T}_d estimated by the disturbance observer includes not only the human pushing force F_{man} but also the effect of the gradient resistance R_s of the road surface. To extract only the human pushing force F_{man} , it is necessary to remove the value of gradient resistance R_s .

The gradient resistance R_s is shown in (7).

$$(M_v + M_F) \cdot g \cdot \sin(\theta) = R_s \quad (7)$$

By multiplying (7) by the wheel radius r_w , it is converted into a torque, which is subtracted from the estimated disturbance \hat{T}_d to compensate for the gradient resistance R_s . In the simulation is obtained without sensors. For the actual experiment, the gradient resistance R_s is calculated as a known value; in the actual implementation, the gradient resistance will be obtained by an accelerometer.

D. Virtual one-wheel drive model

The estimated human pushing force F_{man} is input to the virtual one-wheel drive model. The output generated angular velocity $\hat{\omega}$ is the angular velocity when the virtual one-wheel drive model is pushed by the human pushing force F_{man} . In this research, the virtual one-wheel drive model is set to the value when the one-wheel cart is unloaded. The virtual one-wheel drive model when the one-wheel cart is unloaded becomes (8).

$$\hat{\omega} = \frac{1}{(J_w + M_v \cdot r_w^2)s + B_w} \cdot F_{man} \quad (8)$$

The $\hat{\omega}$ is used as angular velocity command, then, the angular velocity controller adjusts the motor torque through a proportional control.

The block diagram for the controller and the plant model can be shown in Fig. 3.

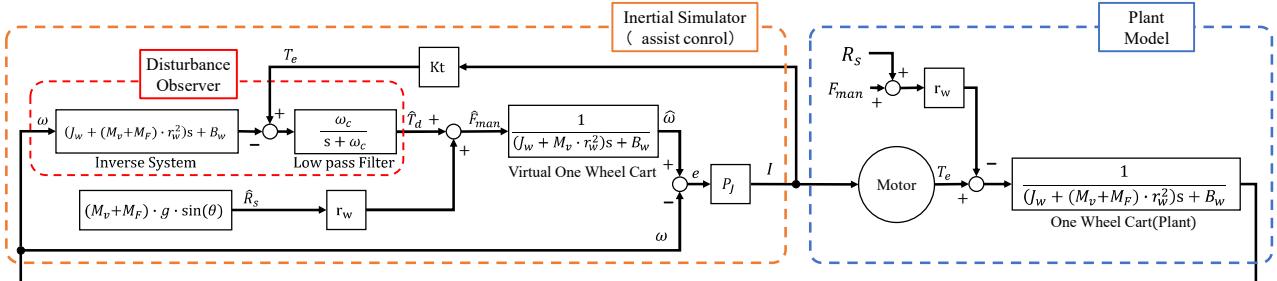


Fig.3 block diagram for the assist control and the plant model

III. SIMULATION OF ASSIST CONTROL

A. Modeling of speed control by the operator

When a operator pushes a one-wheel cart, the operator does not continue to apply a certain amount of force, but rather controls the force so that the one-wheel cart reaches a certain speed. To reproduce this behavior in the simulation, this model the Operator's control of the speed. Proportional gains P_{man} were determined on a trial-and-error basis.

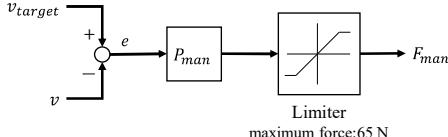


Fig.4 speed control by operator

As shown in Fig.4, the Operator's speed control performs proportional control for the pushing force F_{man} based on the target vehicle speed v_{target} and the vehicle speed v . In addition, the pushing force of the person has a limiter with maximum force value.

B. Simulation

The simulation is performed to validate the assist control using the inertia simulator. The target vehicle speed v_{target} is set to 1 m/s (5.6 rad/s) from 1s. Fig.5 shows a graph of the one-wheel cart's angular velocity vs. human pushing force when the freight is empty. Fig.6 shows a graph when the one-wheel cart is loaded with freight and on a 5 deg gradient, and Fig.7 shows a graph when assist control is enabled under the same conditions as in Fig.6.

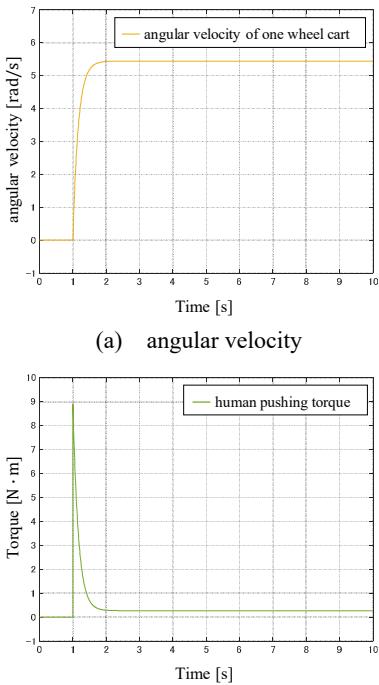
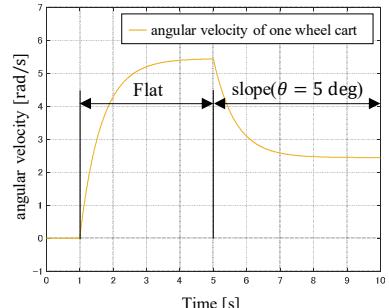
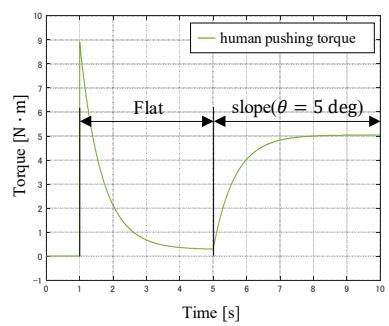


Fig.5 Angular velocity of one-wheel cart and human pushing torque when freight is empty (Flat ground)

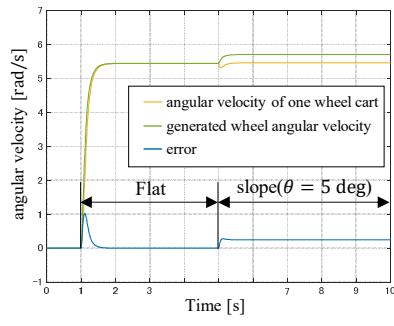


(a) angular velocity

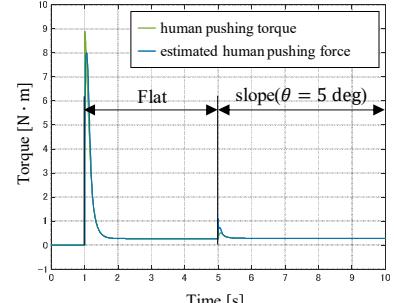


(b) human pushing force

Fig.6 Angular velocity and human pushing torque when loaded with freight and on a slope
(without assist control, slope section from 5 s)



(a) angular velocity



(b) human pushing torque

Fig.7 Angular velocity and human pushing torque when loaded with freight and on a slope
(with control, slope section from 5 s)

IV. SIMULATION RESULTS

Fig.5, Fig.6, and Fig.7 show that when the one-wheel cart is loaded with freight or on a slope, the amount of human pushing force increases compared to when the one-wheel cart is empty. On the other hand, when the

control is enabled under the same conditions, the graph shape is the same as when the freight is empty. This indicates that the inertia simulator worked correctly and achieved the desired behavior.

V. EXPERIMENTAL DEVICE

A. Selection of One wheel car and Motor

Next, verification will be conducted using actual equipment. The one-wheel cart used was made of aluminum for future additional work. The motor to be used is selected. From Fig. 6, it can be seen that the motor requires a maximum torque of 9 Nm and a rotation speed of 5.6 rad/s when the one-wheel cart is loaded with a load. After searching for a motor that satisfies these values, I determined that the PMSM for AGVs sold by Nidec-Simpo Corporation is suitable. Fig.8 shows a photograph of the one-wheel cart and motor used in the actual machine, and Table 2 shows the performance of the motor.



(a) Aluminum one-wheel cart



(b) PMSM

Fig.8 one-wheel cart and motor used in the actual machine

Table 2 Performance of permanent magnet synchronous motors used in actual equipment

Manufacturer	Nidec-Sympo
Model No.	SU065-M4381-G09C0
Rated speed [rpm]	333
Instantaneous maximum speed [rpm]	444
Rated speed [rad/s]	34.9
Rated output torque[Nm]	10.8
Maximum output torque[Nm]	21.8

Table 2 shows that the rated torque of the motor is 10.8 Nm, which meets the required performance. The rated speed of the motor is 5.5 rad/s, which is also considered acceptable. From the above, it can be said that this motor satisfies the performance required for assist control.

B. System configuration

The appearance of a prototype of the one-wheel cart with an electric motor is shown in Fig.9 and the system configuration of the motor drive and the assist controller is shown in Fig.10.

The electric motor for one-wheel cart consists of a motor, control board, angle sensor, acceleration sensor, and operation switch. The control board not only controls the motor but also performs calculations for the inertia



Fig.9 Prototype of the one-wheel cart with an electric motor

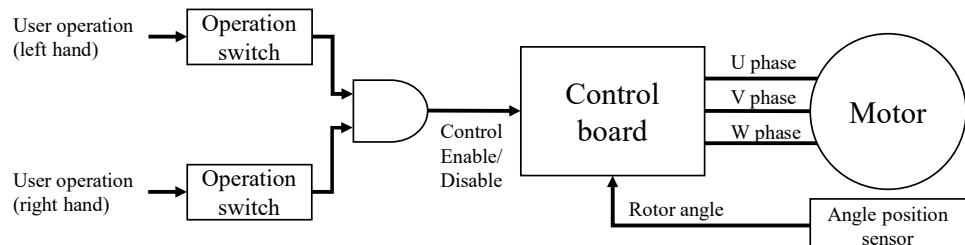


Fig.10 System configuration of the motor drive and the assist controller

simulator. The motor is equipped with an angle position encoder, which transmits the rotor angle of the motor to the control board. The assist control also requires the one-wheel cart wheel angular velocity value, then the wheel angular velocity is calculated from the rotor angle obtained from the angle position attached to the motor. Operating switches are mounted on both handles of the one-wheel cart. The switches are pressed simultaneously with both hands to activate the assist control, and are deactivated when one of the switches is released. The reason for using two control switches is to ensure safety by preventing the one-wheel cart from activating the assist operation at a timing unintended by the user due to incorrect operation.

VI. VALIDATION OF THE INERTIA SIMULATOR

The inertia simulator was verified on an actual electric one-wheel cart. As a condition for verification, the weight of the freight is assumed to be 40 kg. The weight of the freight is assumed to be already known by the controller and no weight sensor is used. A training running machine was used as the load device, simulating a person pushing and moving a one-wheel cart. The running speed command of the training running machine was changed from 1 km/h (1.56 rad/s) to 3 km/h (4.68 rad/s) during the experiments. Fig.11 shows a graph of wheel angle velocity and motor torque when the one-wheel cart was empty of freight, Fig.12 shows a graph of wheel angle velocity and motor torque when the one-wheel cart was loaded with freight, and Fig.13 shows a graph of wheel angle velocity and motor torque when the one-wheel cart was loaded with freight and assist control was enabled.

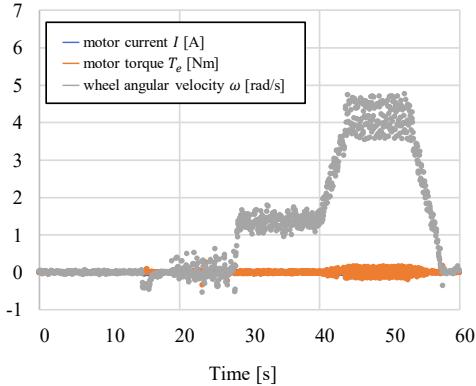


Fig.11 wheel angle velocity and motor torque (unload condition)

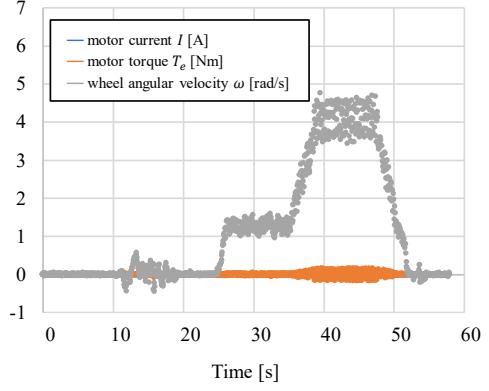


Fig.12 wheel angle velocity and motor torque (load condition without proposed assist control)

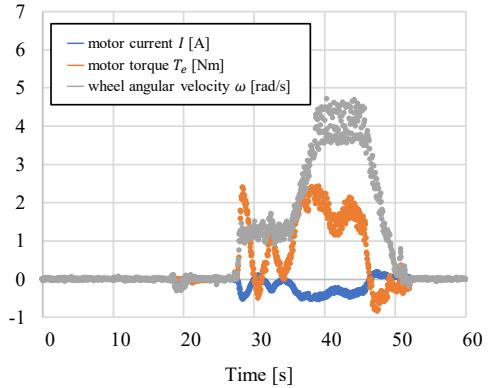


Fig.13 wheel angle velocity and motor torque (load condition with proposed assist control)

Comparing Fig.11 and Fig.12 shows that there is approximately no difference in the time required for the wheel angular velocity ω to reach a steady state when the freight is empty and when the freight is loaded. The reason for this result is thought to be that the running machine itself is equipped with a speed control function to compensate for load fluctuations. Since the assist control is disabled, both motor torque T_e values are found to be around 0 Nm.

From Fig.(13), the motor torque was increased by the assist control when the wheel angular velocity was changed. At the running start and the timing of speed change, the motor torque was controlled to assist the human pushing force as the transient response of the wheel angular velocity. After that, the motor torque was controlled to compensate the friction force of the wheel as steady state. It indicated that the proposed assist control could assist the human pushing force.

VII. CONCLUSION

In the prototype one-wheel cart, the inertia simulator operated correctly in the simulation, and the desired behavior was achieved.

Future plans include measuring the weight of the freight using a weight sensor and improving the control method so that the inertia simulator will operate normally even if the weight of the freight on the one-wheel cart changes. In addition, It is planned to improve the control method so that the inertial simulator can detect the angle of inclination with an accelerometer and operate properly even when the road surface is inclined and subjected to inclination resistance.

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