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Simultaneous estimation of slope angle and handling force when getting on and off a human-riding wheeled inverted pendulum vehicle

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***Abstract*— We are developing a human-riding wheeled inverted pendulum for use as a personal vehicle. To be practically usable, the vehicle requires a function that enables the rider to get on and off both safely and smoothly while on a slope of unknown angle. Concretely, for the convenience of the rider, the vehicle needs to be stabilized on an unknown slope without the rider aboard, both before the rider gets on it and after he/she gets off it. Moreover, the vehicle should be stabilized safely relative to the rider's handling force at a grip of the vehicle while getting on and off. We thus developed a method of estimating the handling force and the slope angle separately. In this paper, we report the method to estimate the handling force and the slope angle using a disturbance observer. We verified the validity of our proposed estimation method by computer simulations and experiments using a prototype of a human-riding wheeled inverted pendulum on an unknown slope.**

I. INTRODUCTION

In recent years, human-riding wheeled inverted pendulum vehicles are being developed for everyday use as interest in small and lightweight riding vehicles increases. Segway [1] was developed in the US in 2001 and has already been sold there and in Japan. In 2004, the PMP-2 [2][3], a riding mobile platform was developed at Japan's National Institute of Advanced Industrial Science and Technology (AIST). Additionally, the i-Swing and Personal Mover were released in 2005 and 2007, and the Mobilo and Winglet [4] were completed in 2007 and in 2008.

There are often many slopes of 10 degrees or more i.e Fig.1 in ordinary environments, so following function would be useful and needed for making a human-riding wheeled inverted pendulum practical for everyday use: The vehicle would remain steady while standing balanced at a position where the rider could get off and move away from it. And the vehicle would stand there upright until the human got on again smoothly. We thus aimed to develop this function and implement it in our prototype vehicle. The problem is the development of functions that would be effective especially on slopes. On a slope, the vehicle will go on the slope downwards because of gravity, even if the center of gravity of the vehicle is right above the center of the two wheels. For this reason, it is difficult for the rider to get on and off smoothly and safely while on a slope. Segway [1] and Winglet [4] don't have the function.

In [5], a wheeled inverted pendulum robot which was not a riding vehicle type, was prevented from going on the slope downwards by using feed-forward torque calculated with the estimated slope angle to maintain the stability of the robot on the slope.However, the control method cannot be suitably applied to a riding wheeled pendulum vehicle because the force added to the vehicle handle when the rider is getting off or on (we call this force the "handling force" in this paper) is counted together with the estimated slope angle. In [6], human's external force to an inverted pendulum robot are estimated by using reduced-order disturbance observer. However, the method are applied only on the horizontal ground and position feedback control are used for the control of the robot. Position feedback control is not suitable for human-riding type vehicle.

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Fig. 1. Moving human-riding-type wheeled inverted pendulum vehicle on slope

In this paper, our simultaneous estimation method of the slope angle and handling force is suggested without using alternative sensors for solution of this problem. And the theoretical proof of the method is indicated herein and our estimations are demonstrated by simulations. Furthermore, we report that the method has been implemented in a vehicle [2] to which a handle is attached, and the effectiveness of the method was adequately confirmed in experiments using a real vehicle.

II. HUMAN-RIDING WHEELED INVERTED PENDULUM VEHICLE

A. Target vehicle

Our target vehicle for the development of those functions is the "PMP-2" [2] retrofitted with handles. There are two individual controllable wheels in the body, and the stick-shaped handles are attached vertically at both sides of the body. Two motors and a computer are installed in the body and the upper face of the vehicle is the platform on which the rider stands. The vehicle and rider are shown in Fig.2∼4. The size including the wheels is 425 mm × 550 mm (overall length × overall width) and the weight is approximately 12.6 kg. The height of the rider's platform is 185 mm above the ground, the length of the sticks is 1250 mm and the radius of the wheels is approximately 130 mm.

Both the right and left wheels are driven by DC-motors which are controlled by the on-board computer installed in the vehicle. The angles of both wheels are measured by counting the number of encoder pulses and the angle, and the angular velocity of the pitch direction of the vehicle is measured using gyro-sensors and an accelerometer. A force sensor attached to the platform of the vehicle detects whether the rider is on or off.

B. Three states of the vehicle including the rider's action of getting on and off

When getting on the vehicle, the rider first keeps the platform horizontal using the handles, and then lifts one leg after the other to step up onto the platform. When getting off the vehicle, the rider reverses this movement and puts down one leg at a time onto the ground while grasping the handles. After rider gets off the vehicle, it should stand still at the position where the rider got off and should stand there balanced and upright until the rider gets on it again.

The connections of rider and vehicle are divided into three states, state A: when the human is riding on the vehicle; state B: when only the handles are being grasped and supported by the human while getting off and on; and state C: when the vehicle maintains a balanced and stable posture. State B includes the motion of the rider's just getting on and off. State A changes to state C through state B definitely. The change from state C to state A is the same as passing through state B, when the rider is getting on or off. State A is shown in Fig.2, state B is shown in Fig.3 and state C is shown in Fig.4.

Fig. 2. state A: human riding on the vehicle

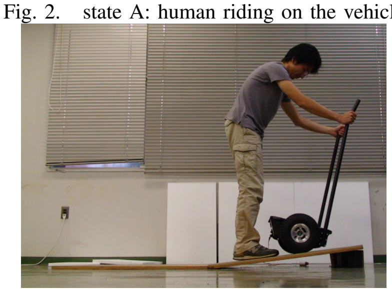

Fig. 3. state B: handling force is added by human when getting on or off

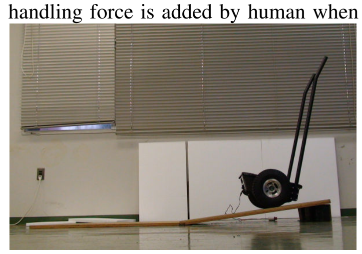

Fig. 4. state C: the vehicle maintains a balanced posture and stands still

C. Problems when getting on and off on an unknown slope

The state linear feedback control method is very efficient for controlling wheeled inverted pendulum vehicles and this method has been applied in many research works [2][5][7][8][9]. For a human-riding wheeled inverted pendulum vehicle, it is better not to add traveling position feedback to the state linear feedback control. Because steady-state errors affect the posture angle of the vehicle with a rider aboard and the vehicle posture could become off-vertical that is not comfortable for riding.

The vehicle's center of gravity has been adjusted to be above of the center of the wheels when the platform is horizontal. However, in state C, the vehicle goes on the slope downwards without grasping the handle after the rider gets off. The vehicle can't be still at the position where the rider got off. The rider must stay with the vehicle to prevent it from rolling down the slope, so it is inconvenient.

One easy way to solve this problem would be to add position feedback after the rider gets off. The rider's action of getting off or on can be detected using force sensors attached to the platform floor of the vehicle. However the center of gravity of this vehicle is set at a very low position, so large feedback gains are needed to keep the falling distance small and to prevent the rider's legs from being injured. In that situation, the rider would tend to add some force to the handle and body when getting on the vehicle, so the vehicle would easily move, and then large feedback torque would generated due to the feedback of the position. As a result, the vehicle might possibly get out of control because of the divergence of the feedback control system. Furthermore, the rider would add some force at the handle to control and reduce the falling and out-of-control motion of the vehicle, which would further promote the divergence of the feedback system. For that reason, although position feedback would be able to solve the problem in state C, state B including the action of the rider's getting off or on would be more unstable and dangerous.

The important issue about the rider getting on and off on a slope is that the vehicle cannot keep its balance and stand still safely on the slope during both state C and state B continuously. Thus, we have suggested the following functions. Slope angle and handling force are estimated simultaneously in the vehicle with the handling force. And feed-forward torque is generated and added to compensate to maintain the vehicle's balance and keep it standing still on the slope. A demonstration of safely getting off and on will be performed using those functions with our vehicle.

III. Dynamics of vehicle with handling force on a slope

A. Dynamic modeling

The wheeled inverted pendulum with handling force but without a rider aboard in state B and state C is treated to dynamic modeling. The sagittal dynamics model on moving forward and back is assumed to be a two-dimensional model with handling force on the slope for the purpose of designing the estimator. The shape of the vehicle is modeled to the two links shape shown in Fig.5 : one is the wheel shape, the other is the stick shape. The force effected at each joint and contact point is described using Lagrange multipliers, and the equations of the dynamics are derived by using the multi-body dynamics method. The second differential state variables in the equations of the dynamics are defined as follows.

$$\ddot{\mathbf{P}} = \begin{bmatrix} \ddot{x_1} \\ \ddot{y_1} \\ \ddot{x_2} \\ \ddot{y_2} \\ \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} \begin{matrix} acceleration\ of\ Link\ 1\ on\ x\ axis \\ acceleration\ of\ Link\ 1\ on\ y\ axis \\ acceleration\ of\ Link\ 2\ on\ x\ axis \\ acceleration\ of\ Link\ 2\ on\ y\ axis \\ angular\ acceleration\ of\ Link\ 1\ to\ the\ ground \\ angular\ acceleration\ of\ Link\ 2\ to\ the\ ground \end{matrix} \tag{1}$$

And the constraint forces are defined as below.

$$\lambda = \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \end{bmatrix} \begin{matrix} constraint\ force\ on\ x\ axis\ of\ link1 \\ constraint\ force\ on\ y\ axis\ of\ link1 \\ constraint\ force\ on\ x\ axis\ of\ link2 \\ constraint\ force\ on\ y\ axis\ of\ link2 \end{matrix} \tag{2}$$

m_1, m_2 and I_1, I_2 represent mass and the inertial moment of each Link1 and Link2 on the center of gravity, and l_1 represent the length from center of the wheel to the center of gravity of Link 1, r is the wheel radius. F is the handling force and l_f is the length from the center of gravity to the position added handling force, the angle of the slope is θ_α, the direction of the handling force is θ_β. The gear ratio of the motor is n and the inertial moment of the rotor in the motor is J_m. Then the equation of the dynamics is derived as follows.

$$\begin{bmatrix} \mathbf{M} & \mathbf{C^t} \\ \mathbf{C} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{P}} \\ \lambda \end{bmatrix} = \begin{bmatrix} \tau \\ \gamma \end{bmatrix} \tag{3}$$

Where, the used characters are shown below.

$$\mathbf{M} = \begin{bmatrix} m_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & m_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & m_2 & 0 & 0 & 0 \\ 0 & 0 & 0 & m_2 & 0 & 0 \\ 0 & 0 & 0 & 0 & I_1+n^2J_m & -n^2J_m \\ 0 & 0 & 0 & 0 & -n^2J_m & I_2+n^2J_m \end{bmatrix} \tag{4}$$

$$\mathbf{C} = \begin{bmatrix} 1 & 0 & -1 & 0 & -l_1\cos\theta_1 & 0 \\ 0 & 1 & 0 & -1 & l_1\sin\theta_1 & 0 \\ 0 & 0 & -1 & 0 & 0 & r\cos\theta_\alpha \\ 0 & 0 & 0 & -1 & 0 & r\sin\theta_\alpha \end{bmatrix} \tag{5}$$

$$\tau = \begin{bmatrix} F\sin\theta_\beta \\ F\cos\theta_\beta - m_1 g \\ 0 \\ -m_2 g \\ -\tau + F l_f \sin\left(\theta_\beta - \theta_1\right) \\ \tau \end{bmatrix} \tag{6}$$

$$\gamma = \begin{bmatrix} -l_1\dot{\theta}_1^2\sin\theta_1 \\ -l_1\dot{\theta}_1^2\cos\theta_1 \\ 0 \\ 0 \end{bmatrix} \tag{7}$$

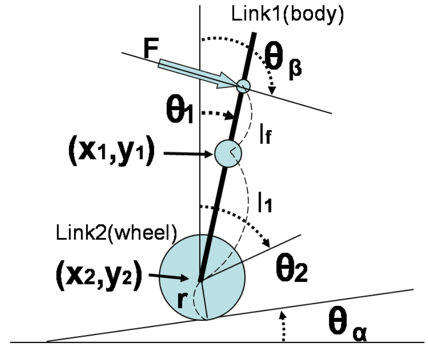

Fig. 5. Modeling of the wheeled inverted pendulum

$\lambda_1, \lambda_2, \lambda_3, \lambda_4$ and $\ddot{x_1}, \ddot{y_1}$ and $\ddot{x_2}, \ddot{y_2}$ are grouped, then the equation of the dynamics are as follows.

$$\alpha_{11}\ddot{\theta}_1 + \alpha_{12}\ddot{\theta}_2 + \gamma_1 = -\tau \tag{8}$$

$$\alpha_{21}\ddot{\theta}_1 + \alpha_{22}\ddot{\theta}_2 + \beta_2\dot{\theta}_1^2 + \gamma_2 = -\tau \tag{9}$$

Where,

$$\alpha_{11} = m_1 {l_1}^2 + J_1 + n^2 J_m \tag{10}$$

$$\alpha_{12} = m_1 r l_1 \cos\left(\theta_1 + \theta_\alpha\right) - n^2 J_m \tag{11}$$

$$\gamma_1 = -m_1 g l_1 \sin\theta_1 - F\left(l_1 + l_f\right)\sin\left(\theta_\beta - \theta_1\right) \tag{12}$$

$$\alpha_{21} = m_1 r l_1 \cos\left(\theta_1 + \theta_\alpha\right) \tag{13}$$

$$\alpha_{22} = \left(m_1 + m_2\right) r^2 + J_2 + n^2 J_m \tag{14}$$

$$\beta_2 = -m_1 r l_1 \sin\left(\theta_1 + \theta_\alpha\right) \tag{15}$$

$$\gamma_2 = \left(m_1 + m_2\right) r \sin\theta_\alpha - F r \sin\left(\theta_\beta + \theta_1\right) \tag{16}$$

B. Linearization of the dynamics

Viscous friction $fr(\dot{\theta}_2 - \dot{\theta}_1)$ between the body and wheel is added to the equations (8) and (9), then accounting for the motion near the balancing posture, the following linearization is applied. $\sin\theta_1 \simeq \theta_1$, $\cos\theta_1 \simeq 1$, $\cos(\theta_1 + \theta_a) \simeq 1$, $\dot{\theta}_1^2 \simeq 0$. The handling force is assumed to be added in the vertical direction to the handle then $\sin\theta_\beta \simeq 1$. The equations (8) and (9) are linearized as follows.

$$\mathbf{A}\begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} + \mathbf{B}\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} + \mathbf{H}\begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix} + \mathbf{E} = \mathbf{D} \tag{17}$$

where

$$\mathbf{A} = \begin{bmatrix} m_1 {l_1}^2 + J_1 + n^2 J_m & m_1 r l_1 - n^2 J_m \\ m_1 r l_1 - n^2 J_m & (m_1+m_2) r^2 + J_2 + n^2 J_m \end{bmatrix} \tag{18}$$

$$\mathbf{B} = \begin{bmatrix} f_r & -f_r \\ -f_r & f_r \end{bmatrix}, \quad \mathbf{H} = \begin{bmatrix} -m_1 l g & 0 \\ 0 & 0 \end{bmatrix} \tag{19}$$

$$\mathbf{E} = \begin{bmatrix} 0 & -F(l_1 + l_p) \\ r\sin\theta_\alpha (m_1 + m_2) g & -rF \end{bmatrix} \tag{20}$$

$$\mathbf{D} = \begin{bmatrix} -\tau \\ \tau \end{bmatrix} \tag{21}$$

IV. Simultaneous estimation of slope angle and handling force

A. Objective

In this section, our objective is to estimate the slope angle without the effectiveness of the handling force for giving feed-forward torque depending on the slope angle, in state B or state C without the rider aboard. A human-riding wheeled inverted pendulum vehicle is added several handling forces. There is a large and different characteristic from only an inverted pendulum, so the handling force must be considered. Thus, the angle of the slope and handling force are divided and estimated simultaneously and the estimated values are applied for control.

B. Separation of slope angle and handling force in estimation using output torque

Simultaneous estimation of the angle of the slope and handling force are calculated using the difference of the output motor torque during ordinary use on horizontal ground from the output motor torque for the vehicle with the handling force on the slope. The interesting issue of this method is that double values for both the slope angle and handling force can be derived from the single value on the difference of torque if the angle and angular velocity of the vehicle are measured and torque for control are given.

When the vehicle is standing still with handling force on the slope, $\ddot{\theta}_1 = \ddot{\theta}_2 = \dot{\theta}_1 = \dot{\theta}_2 = 0$ and (8), (9) become as follows.

$$\gamma_1 = -\tau \tag{22}$$
$$\gamma_2 = \tau \tag{23}$$

The output torque τ and posture angle of the vehicle θ_1 are given to (22) and (23), then there are two unknown values (F, θ_α) and two constraint equations in (22), (23). Thus, it is possible to derive two individual values simultaneously from the single value.

C. Designing of a estimation method by applying disturbance observer

We have designed an estimator by applying a disturbance observer to obtain the slope angle and handling force simultaneously not only while the vehicle is standing still but also while the vehicle is moving. The estimated values are defined as follows.

$$\hat{\mathbf{X}} = \begin{bmatrix} \hat{\theta}_1 \\ \hat{\theta}_2 \\ \dot{\hat{\theta}}_1 \\ \dot{\hat{\theta}}_2 \\ \sin\hat{\theta}_\alpha \\ \hat{F} \end{bmatrix} \begin{array}{c} Estimated\ position\ angle\ of\ Link1 \\ Estimated\ position\ angle\ of\ Link2 \\ Estimated\ angular\ velocity\ of\ Link1 \\ Estimated\ angular\ velocity\ of\ Link1 \\ Estimated\ angular\ of\ slope \\ Estimated\ handling\ force \end{array} \tag{24}$$

And, the values measured from sensors are defined as

$$\mathbf{Y} = \begin{bmatrix} \theta_1 \\ \theta_2 - \theta_1 \\ \dot{\theta}_1 \\ \dot{\theta}_2 - \dot{\theta}_1 \end{bmatrix} \begin{array}{c} posture\ angle\ of\ Link1 \\ angle\ between\ Link1\ and\ Link2 \\ angular\ velocity\ of\ Link1 \\ angular\ velocity\ between\ Link1\ and\ Link2 \end{array} \tag{25}$$

Then output equation is derived as follows.

$$\mathbf{Y} = \mathbf{CX}, \quad \mathbf{C} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 \end{bmatrix} \tag{26}$$

$\mathbf{X}$ is the same type of value as $\hat{\mathbf{X}}$ but was not estimated. We assumed that the angle of the slope did not change largely in a short time, then

$$\frac{d}{dt}\sin\theta_\alpha = 0 \tag{27}$$

And the state equation becomes

$$\dot{\hat{\mathbf{X}}} = \hat{\mathbf{A}}\hat{\mathbf{X}} + \hat{\mathbf{B}} \tag{28}$$

Where

$$\hat{\mathbf{A}} = \begin{bmatrix} 0 \quad 0 & 1 \quad 0 & 0 \quad 0 \\ 0 \quad 0 & 0 \quad 1 & 0 \quad 0 \\ (-\mathbf{A}^{-1}\mathbf{H}) & (-\mathbf{A}^{-1}\mathbf{B}) & (-\mathbf{A}^{-1}\mathbf{E}) \\ 0 \quad 0 & 0 \quad 0 & 0 \quad 0 \\ 0 \quad 0 & 0 \quad 0 & 0 \quad 1 \end{bmatrix} \tag{29}$$

$$\hat{\mathbf{B}} = \begin{bmatrix} 0 \\ 0 \\ \mathbf{A}^{-1}\mathbf{D} \\ 0 \\ 0 \end{bmatrix} \tag{30}$$

The designed full-order observer is as follows.

$$\dot{\mathbf{X}} = (\hat{\mathbf{A}} - \mathbf{KC})\hat{\mathbf{X}} + \mathbf{KY} + \hat{\mathbf{B}} \tag{31}$$

$\mathbf{K}$ is $[6 \times 4]$ dimensional matrix and it is calculated with vector $\mathbf{P_o}$ including six poles using MATLAB functions

$$\mathbf{K} = \left(place(\bar{A}^T, C^T, \mathbf{P_o})\right)^T \tag{32}$$

The rank of observability matrix is defined as

$$\mathbf{U} = \begin{bmatrix} \mathbf{C} & \mathbf{C}\hat{\mathbf{A}} & \mathbf{C}\hat{\mathbf{A}}^2 & \mathbf{C}\hat{\mathbf{A}}^3 & \mathbf{C}\hat{\mathbf{A}}^4 & \mathbf{C}\hat{\mathbf{A}}^5 \end{bmatrix}^T \tag{33}$$
$$rank(\mathbf{U}) = 6 \tag{34}$$

Thus, we can estimate all the values of $\mathbf{X}$ from dates $\mathbf{Y}$ with the sensors by using the disturbance observer.

D. Simulation results

We configured the simulator based on the dynamics (8) and (9). The torque was calculated by linear state feedback control for the input of control to the model in the simulator. The parameters used in the simulator were measured based on the vehicle and those are shown in the following.

$m_1 = 12.6$	$m_2 = 2.0$		[kg]
$l_1 = 0.075$	$l_f = 0.8$	r=0.13	[m]
$J_1 = 0.252$	$J_2 = 0.0168$	$J_m = 3.4200e-05$	$[kgm^2]$
n=50			

10 deg was given for the slope angle and a sin function shown in the last of Fig.6 was given for the handling force for the simulation of the simultaneous estimation of the slope angle and handling force. Our estimated results of the slope angle θ_a and handling force $\hat{F}$ and given handling force F are shown with in order from the top in Fig.6.

The estimated slope angle θ_α reached 80% of the given value for the slope angle in 0.5 sec from the start and it converged almost 10 degrees stably in 1 sec. The estimated handling force was 0.5 sec behind the given one and it converged at almost the same values. We can confirm that both the slope angle and handling force were estimated simultaneously and that the estimated slope angle had no influence on the handling force in the simulations.

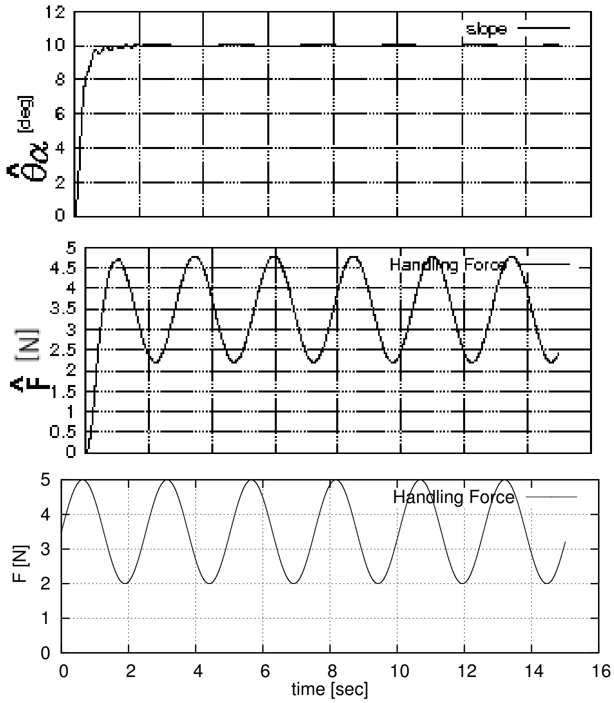

Fig. 6. Estimated $\hat{\theta}_{\alpha}$ and $\hat{F}$, given F in simulation

V. Experiments with the real vehicle

A. Observer gain matrix

The gain matrix calculated using the six minus pole $\mathbf{P_o}$ worked well in our simulations, however we need to be careful when deciding approximate gains in our experiments with the real vehicle. We searched the gain matrix by changing $\mathbf{P_o}$ until the estimated result fit one experimental result $\mathbf{Y}$. The selected matrix gain worked well even in several other experiments, and the gain matrix is shown below.

$$\mathbf{K} = \begin{bmatrix} 8.5160 & 0.6761 & 0.8892 & 0.0096 \\ 7.6184 & 10.1528 & 0.1460 & 1.0294 \\ -0.1774 & -3.8860 & 12.4981 & -0.2502 \\ 77.9236 & -68.8679 & 9.0626 & 14.6191 \\ -12.7583 & 8.6914 & -0.4357 & -0.9763 \\ -106.2923 & -83.8959 & 94.7111 & -0.7711 \end{bmatrix}$$

B. Non-linear friction between body and wheel

It was most important to deal with the nonlinear friction closely between the body and wheel for approximate estimations in the real vehicle using this method. If the friction is not counted, the estimation did not work at all, because the order of value of the torque for control is almost same as the order of the value of the friction. f_r in (19) was given 0 and the torque of friction were given as the model of following nonlinear function for the estimation in the vehicle.

$$\begin{aligned} I_{frc} &= a_2 \tanh\left(a_0\left(\dot{\theta}_2 - \dot{\theta}_1\right)\right) + a_1\left(\dot{\theta}_2 - \dot{\theta}_1\right) && (35) \\ \tau_{frc} &= I_{frc} \times \ (torque\ Constant) \times (gear\ ratio) && (36) \\ a_0 &= 12.9439, \quad a_1 = 0.1936, \quad a_2 = 0.61 \end{aligned}$$

The friction torque (36) is reduced from the output torque τ.

C. Control method using the estimated angle of the slope

Different control methods were applied to state A with riders and state B or state C without riders. Feed-forward torque was added in state B and state C but not in state A. The judgement on whether a rider was on or off the vehicle was done using pressure sensors attached to the platform of the vehicle.

$$\begin{aligned} \tau &= K_1\left(\theta_1 - \theta_{1ref}\right) + K_2\dot{\theta}_1 + K_3\dot{\theta}_2 + \tau_{\alpha} && (37) \\ \theta_{1ref} &= (m_1 + m_2)\, rg \sin\theta_{\alpha} / (m_1 l g) && (38) \\ \tau_{\alpha} &= (m_1 + m_2)\, rg \sin\theta_{\alpha} / (n \times : the\ gear\ ratio) && (39) \end{aligned}$$

When there is not a rider on the vehicle in state A, $\theta_{1ref} = 0$ and $\tau_{\alpha} = 0$.

D. Experimental results

We prepared a 9-degree slope connected to a horizontal space for the experiments and the following performance tests were conducted. The rider grasped the handle and put the vehicle which was standing still on the horizontal space facing up the slope and then loosened his grip on the slope. The vehicle was expected to keep its balance and stand still there. Next, the rider grasped the handles and got on the vehicle on the slope. The vehicle moves back and forward with the rider, and then the rider gets off and loosens his grip again on the slope. Then the vehicle is expected to stand still again on the slope. Finally the rider gets on the vehicle on the slope and the vehicle moves to the horizontal space with the rider and the rider gets off and loosens his grip and lets the vehicle stand still again on the horizontal ground. The terms of these motions are shown by the arrows at the top in Fig.8. The results of these experiments are shown in Fig.7 and the estimated results of θ_{α} and F are shown in Fig.8. The term of the vehicle on the slope is from over 0.6 m of distance and from about 17 sec to 60 sec in Fig.7. The other term (i.e start and end) is on horizontal ground. The estimated slope angle and handling force were set to 0 in Fig.7 in terms of state A.

Though the estimated slope angles θ_{α} include oscillation of ± 1deg, the results became approximate 9 deg and almost same as the real angle of the slope. The handling force F was estimated soon after the vehicle is started to face up the slope with the handle. The value of the handling force which is represented as torque is same order as the torque which is needed to keep the vehicle standing on the slope. We succeeded in performing smooth and safe motions of getting off and on the vehicle using feed-forward torque with the estimated slope angle. The estimated angle of the slope showed approximate 3 deg after 60 sec though the vehicle was on the horizontal ground, and the estimated handling force showed 1N though the rider had loosened his grip. We hope that the estimated results can be improved in the future, however they are not serious issues for our demonstration. In fact, they can be neglected using offset and dead-band. We confirmed that the simultaneous estimation of the slope angle and handling force was possible using our method and that the accuracy of our estimated results was adequate for use in the control method for these experiments.

VI. Conclusion

We suggested a method of simultaneous estimation of the slope angle and handling force on an unknown slope for the purpose of improving the safety of a rider getting on and off a human-riding wheeled inverted pendulum vehicle. We confirmed the effectiveness of the method not only in simulations but also in experiments using a real vehicle. An estimation method applying a disturbance observer was suggested and its effectiveness was confirmed in the simulator. Appropriate matrix gain was defined with the dynamics of the real vehicle and we implemented an estimation algorithm that included compensation of the viscus friction between the body and wheels. We conducted experiments with riders getting off and on the vehicle on a slope. In our experiments, not only did we conduct the estimation but we also implemented a control method to prevent the vehicle from rolling down the slope, and safe and smooth motions of the rider getting off and on the vehicle were performed. From these results, we confirmed the effectiveness of our suggested estimation method with a real vehicle. In the future, to further increase rider safety when getting on and off the vehicle, we intend to improve the accuracy of the results of our estimations, develop a control method using handling force, and debug the small various errors in the estimated values.

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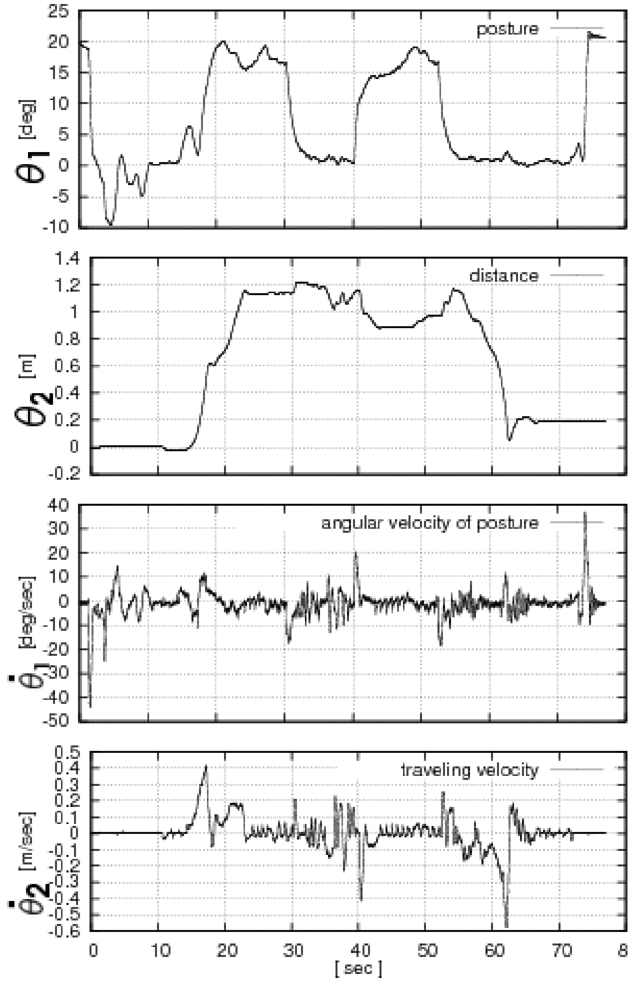

Fig. 7. Measured $\theta_1 \theta_2 \dot{\theta}_1 \dot{\theta}_2$ by sensors in a experiment

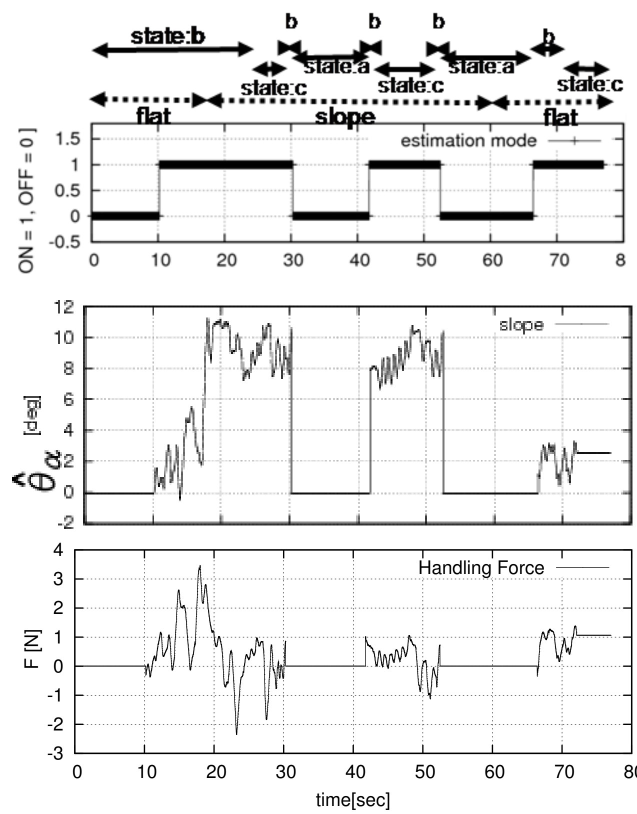

Fig. 8. Estimated $\hat{\theta}_\alpha$ and F in a experiment