Optimal posture control of two wheeled inverted pendulum robot on a slanted surface

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Abstract: Most of the conventional researches are concentrated on the compensation algorithm of the gyroscope signal and posture control on the flat ground. But Segway has been considered as next the generation vehicle, and as its application spread out to the whole of society, its stability and optimal posture on the slanted surface has been discussed worldwide. So, this paper proposes an optimal posture of two wheeled inverted pendulum robot on a slanted surface.

In order to realize posture balance on the slanted surface, tilted weight should be compensated by the proposed algorithm. Dynamic state equation was derived from the system's structure, and an LQR regulator was designed based on the tilted angle obtained from the ultra-sonic sensor. Optimal posture control experiment was iterated as the slanted angles varied. Effectiveness of the proposed algorithms has been verified and demonstrated through simulations and real experiments.

Keywords: Two - Wheel Inverted Pendulum Robot, Optimal Posture Control, ARS (Attitude Reference System).

I. INTRODUCTIION

Conventional researches are highly concentrated on the posture control under ideal environment,[1] but posture control for the slanted surface was not studied. According to the social needs of the next generation vehicle, this paper proposes an optimal posture control of the two wheeled inverted pendulum not only on the flat ground but also on the slanted environment. From the experimental results of the proposed algorithm, the difference between the conventional compensation algorithm and proposed algorithm has been presented.

Finally, optimal posture for the climbing movement from the ARS(Attitude Reference System) will be presented Optimal posture was defined as a stability of the mobile robot during climbing on a slanted surface. This paper consists of five sections including introduction. In Section 2, the modeling of the proposed robot structure and controller design scheme are described, and in Section 3, climbing a slanted surface algorithm will be stated. In Section 4, experimental environment and its results are shown. Conclusions and future research plans are illustrated in Section 5.

II. Modeling of The robot structure and Design of Controller

Dynamics modeling from the proposed structure has been proposed. Fig. 1. illustrates the structure of the inverted pendulum. And table 1 shows each parameters for the mobile inverted pendulum

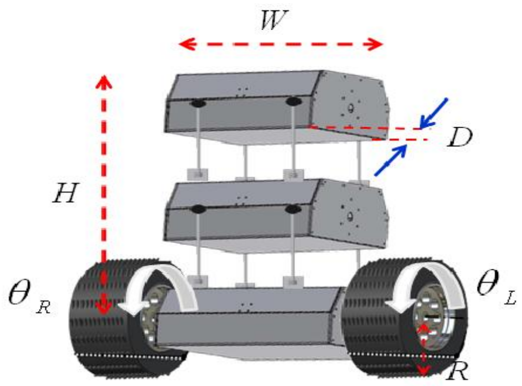

Fig. 1. Two wheeld inverted pendulum.

Table 1. Each parameters for the mobile inverted pendulum

θ	The angle of rotation of wheel from the center
ϕ	A tilted angle of body from the center
β	The angle of rotation of body from rotation of wheel
M_B	The mass of the body
M_W	The mass of the wheel

l	Distance from center of the body to center of the wheel
I_B	Rotation Inertia of the body
I_W	Rotation Inertia of the wheel
μ_s	The coefficient of friction of bearing from wheel
μ_g	The coefficient of friction of the ground from wheel

2.1 Dynamics

Dynamics for the given system has two kinds of parameters, body angle, and wheel angle. Equation (1) shows the dynamics according to the β, θ

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \beta'}\right)-\left(\frac{\partial T}{\partial \beta}\right)+\left(\frac{\partial U}{\partial \beta}\right)+\left(\frac{\partial D}{\partial \beta'}\right)=Q_\beta \quad (1)$$

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \theta'}\right)-\left(\frac{\partial T}{\partial \theta}\right)+\left(\frac{\partial U}{\partial \theta}\right)+\left(\frac{\partial D}{\partial \theta'}\right)=Q_\theta \quad (2)$$

T : Kinetic energy D : Disturbances

U : Potential energy Q : generalized force

T,U,D,Q for the Euler-Lagrange dynamics has been derived as follow,

$$T=\frac{1}{2}M_W(S_2'+Z_2')+\frac{1}{2}M_B(S_1'+Z_1') +\frac{1}{2}I_W\theta'+\frac{1}{2}I_B(\theta'-\beta')+\frac{1}{2}I_M\eta^2\beta' \quad (3)$$

$$U=M_W gr+M_B gl\cos(\theta-\beta) \quad (4)$$

$$D=\frac{1}{2}(\mu_s\beta'+\mu_g\theta') \quad (5)$$

$$Q_\beta=u, Q_\theta=0 \quad (6)$$

We can attain following equations by plugging both the kinetic energy and potential energy to the equation (1) and (2), then

$$\begin{bmatrix}(M_Bl^2+I_B+I_M\eta^2)\phi'' \\ +(M_Brl\cos\phi-I_M\eta^2)\theta'' \\ +\mu_S\phi'-\mu_S\theta'-M_Bgl\sin\phi+u\end{bmatrix}=0 \quad (7)$$

$$\begin{bmatrix}(M_Brl\cos\phi+M_Bl^2+I_B)\phi'' \\ +((M_B+M_W)r^2+M_Brl\cos\phi+I_W)\theta'' \\ -M_Brl\phi'\sin\phi+\mu_S\theta'-M_Bgl\sin\phi\end{bmatrix}=0 \quad (8)$$

System dynamics could be expressed as equation (7), and (8).

2.2 Controller design

From the dynamic analysis for the proposed structure, the linearized dynamic equation could be derived as follow. Non-linear dynamic equation (7) and (8) could be linearized as (9).

$$\theta''=\frac{-O\theta'+P\phi'+Q\phi'+Ru}{W}$$
$$\phi''=\frac{S\theta''-T\phi'+U\phi-Vu}{W} \quad (9)$$

Equation (10) shows the generalized state space equations.

$$x'(t)=Ax(t)+Bu(t)$$
$$y(t)=Cx(t) \quad (10)$$

Representing the robot structure to the state space equations, then (11) could be attained.

$$x=\begin{bmatrix}\theta\\ \theta'\\ \phi\\ \phi'\end{bmatrix},\ \begin{bmatrix}\theta'\\ \theta''\\ \phi'\\ \phi''\end{bmatrix}=\begin{bmatrix}0 & 1 & 0 & 0\\ 0 & -\frac{O}{W} & \frac{Q}{W} & \frac{P}{W}\\ 0 & 0 & 0 & 1\\ 0 & \frac{S}{W} & \frac{T}{W} & \frac{U}{W}\end{bmatrix}\begin{bmatrix}\theta\\ \theta'\\ \phi\\ \phi'\end{bmatrix}+\begin{bmatrix}0\\ R\\ 0\\ -V\end{bmatrix}u$$

$$y=\begin{bmatrix}1 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}\theta\\ \theta'\\ \phi\\ \phi'\end{bmatrix} \quad (11)$$

The LQR controller from the equation (11) was designed by Simulink. Its figure is illustrated in Fig. 2.

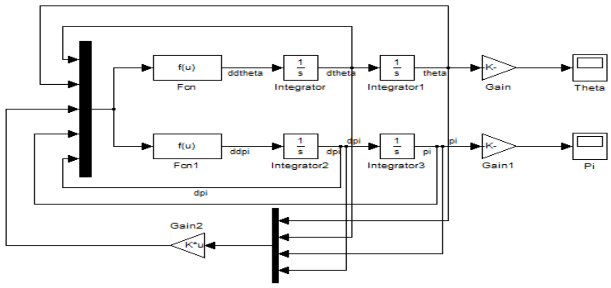

Fig. 2. LQR controller design

III. Climbing a slanted surface algorithm

During the climbing control of the robot, unexpected disturbance forces are essentially caused by the irregular contact force which comes from the irregular contact angle between the wheel and the terrain.[2] The disturbances have effects on the optimal posture of the mobile robot to compensate the slanted angle. So, In order to realize posture balance on the slanted surface, tilted weight should be compensated by the proposed algorithm.

Table 2. Robot parameters for the slanted surface

M_W	The mass of the wheel
g	acceleration of gravity
l	Distance from the body center of gravity
s	Moving distance of the mobile robot
f_c	Coefficient of friction with the slop
F	External force to the mobile robot
N	External force to the actuator from the robot body
α	Slope angle

Table 2 describes the robot parameters while climbing a slanted surface. The governing equation for the flat ground for the equilibrium state was derived in equation (12).

$$F = M_W s'' + M_W g \sin\alpha + f_C \cos\alpha - N \qquad (12)$$

The governing equation for the slanted ground for the equilibrium state was derived in equation (13).

$$F = (M_W + M_B)s'' + M_B l\phi'' \cos\phi$$
$$- M_B l\phi^2 \sin\alpha + M_W g \sin\alpha + f_C \cos\alpha s' \qquad (13)$$

Assuming that ϕ is a tiny enough value to ignore, we can simplify $\phi = 0,\ \sin\phi = \phi,\ \cos\phi = 1$ (14)

Inserting (14) into (13), then we can attain equation (15) as follows.

$$F - M_W g \sin\alpha = (M_W + M_B)s'' + M_B l\phi'' + f_C s' \qquad (15)$$

For the difference between a pre-linearized equation and linearized equation, $M_W g \sin\alpha$ should be compensated a under slated environment.

So, if the ground is tilted to the amount of α, the posture control of the mobile robot on the slanted surface could be realized by compensating amount of $M_W g \sin\alpha$. We can establish a driving command of $M_W g \sin\alpha + \beta$ where β stands for the moving direction's tilted angle.

IV. Experiment

The proposed system consists of a two-wheeled Inverted Pendulum Robot shown in Fig. 7. The body of a mobile robot is designed with two-wheels and motor drive controllers. The controller-related hardware is composed of MCU (Micro Controller Unit, DSP-28335), a gyro sensor, an accelerometer and an ultrasonic sensor

Fig. 3. The configuration of the two-wheeled-inverted robot system

The experiment for driving of the two- wheeled inverted pendulum robot, was conducted on two different environments; when giving a disturbance to the robot on the ground, and when driving on slanted surfaces of 5°,10°,15°,20°,25°. In addition, Fig. 4 shown that the slope was slanted using a clinometer.

Fig. 4. The experiment environment for climbing on the slanted surface.

Using an ultrasonic sensor located under the robot, which receives the distance information from the ground, it is possible to expect information of the slope degree between the ultrasonic sensor and the ground.

Below, Table 3 shows the changed slope angle information from the distance obtained by the ultrasonic sensor.[3]

Table 3. conversion of the angle from distance between the ultrasonic sensor and the ground

Angle (Degrees)	Distance (Centimetres)
0 °	10 cm
5 °	8.5 cm
10 °	7.0 cm
15 °	5.5 cm
20 °	4.0 cm
25 °	2.5 cm
30 °	1.0 cm

The result when given disturbance to the robot on the ground is shown in Fig. 5, and the environment like Fig. 4 shows driving test results at Fig. 5 and Fig. 6. , 7.

The current measured angle from the slope randomly gave 5° more; it was made the two-wheeled Inverted Pendulum Robot can be driven on slope. And When the robot completed climbing at the slope, the two-wheeled inverted pendulum robot can be stopped by converging back to the current angle of the slope. Below, the results shows the current slope values of the acceleration sensor, and target values. Sampling Time is the horizontal axis and the vertical axis represents the Slope Angle.

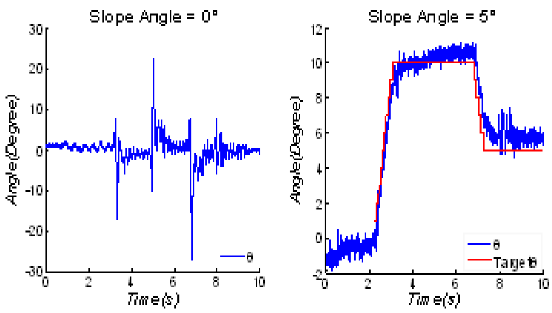

Fig. 5. Driving on an even surface and a 6 degree slope

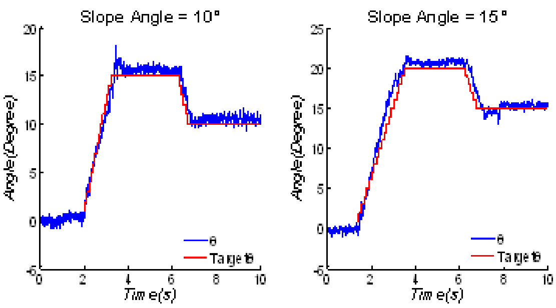

Fig. 6. Driving on a 10 and 15 degree slope

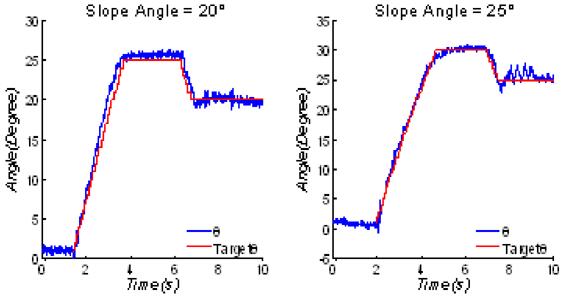

Fig. 7. Driving on a 20 and 25 degree slope

VI. Conclusion

In this paper, when controlling the two-wheel-inverted Pendulum on the slanted environment, we acquired the slope information using the ultrasonic sensor. By varying the operating point of the inverted pendulum and compensating gravity as per the lean of operating point, even the slanted environment, can be controlled for optimal posture. And also, The equation of motion was suggested to satisfy driving speed of the two wheeled robot and slope angle conditions according to the angle of the slope. Therefore, the results of this study will prove useful not only for the mechanism of the two-wheel-inverted Pendulum but also in determining the slope of various other types of wheeled type mobile robot mechanisms.

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