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Navigation of an Inverted Pendulum Type Autonomous Mobile Robot with an Adaptive Stabilization Control System

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Abstract

We develop a wheeled inverted pendulum type mobile robot which can navigate autonomously while keeping its own balance. In this paper, we propose a robust locomotion control system for the inverted pendulum robot, which changes its control mode automatically according to the changes of operating conditions or its dynamics. This paper also reports the results of the navigation of the experimental inverted pendulum robot on which the proposed algorithm is implemented in the real indoor environment.

1. Introduction

We developed a wheeled inverted pendulum type self-contained autonomous mobile robot which can navigate in a real world environment while keeping its balance. Some previous research on wheeled inverted pendulum type robots have been reported [1][2][3][4]. However, we could not find a report on sensor based navigation which was successful by such a robot. We have already reported on a trajectory control algorithm [5] for navigation of such a robot and succeeded in an ultrasonic sensor based indoor navigation experiment using our experimental inverted pendulum type autonomous mobile robot "Yamabico Kurara".

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However, It was found through experiments that the algorithm [5] was not adaptive enough to changes of its operating conditions or dynamics. In navigation experiments using a small type mobile robot, when the robot drives off a given course due to an error, the operator sometimes may have to pick up the robot and place it upon the desired path. Also, the robot may collide with obstacles because of the change of environment and the shortage of external sensor capability. In these cases, the inverted pendulum robot with the control algorithm [5] may fail to keep its balances. To adapt such situations, the robot should observe its own dynamics and parameters of the controller should be reset.

In this paper, a new adaptive locomotion control algorithm for an inverted pendulum robot is proposed, which changes its control mode autonomously according to the observed operating conditions or dynamics. The most important point of this algorithm is to discriminate its model among the possible models in real time and to switch its control mode autonomously. The proposed algorithm is implemented on the experimental robot "Yamabico Kurara", and navigational experiments have been performed in the real indoor environment.

2. Inverted Pendulum Robot Platform "Yamabico Kurara"

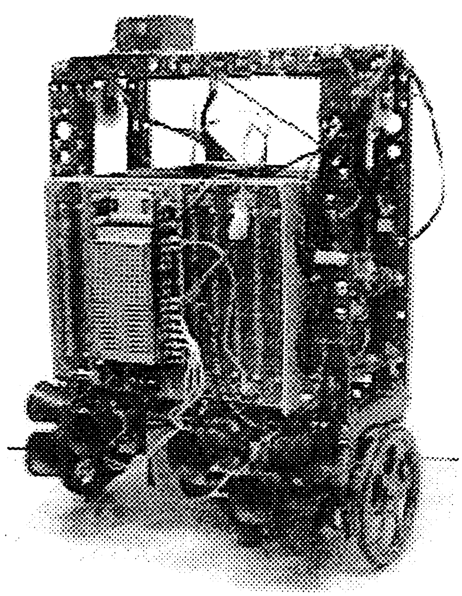

Fig. 1 The inverted pendulum type self-contained mobile robot "Yamabico Kurara"

Yamabico [6] is a series of self-contained autonomous mobile robot platforms for experimental research which were developed by the authors' group. The inverted pendulum robot used for the experiment in this research is ``Yamabico Kurara''. It is a standard type Yamabico robot from which the front and rear casters had been removed. Fig. 1 shows Yamabico Kurara which is controlling itself to keep its own balance. Yamabico Kurara is treated as a target robot for the analysis and controller design in this research.

This robot has rotary encoders (resolution:2000) and a vibration type gyro sensor (TOKIMEC Co. TFG-160) to measure wheel rotation and the body's inclination angular velocity. Both wheels are driven by DC motors of 10 Watts. Ultrasonic range sensors to recognize the environment are attached on the front, left and right sides of the body.

3. The problems in real world navigation

We have reported on the trajectory control algorithm [5] for navigation of Yamabico Kurara and succeeded in an ultrasonic sensor based indoor navigation experiments. As a result, the robot showed very stable traveling if it could navigate successfully in the given environment.

However, it was found through experiments that the inverted pendulum robot with a fixed-parameter controller is not adaptive enough to changes of operating conditions or its dynamics. For example, when the robot drove off the course due to an error in its program or map, the operator sometimes had to pick up the robot and place it upon the desired path. Also, the robot might collide with obstacles because of the environment change and the shortage of external sensor capability. In these cases, the robot failed to keep its balance because of the dynamics change caused by collisions or being lifted-up. Hence, an enhanced locomotion control algorithm which can cope with the change of operating conditions or dynamics is required for realizing more robust navigation.

4. Adaptive stabilization control using on-line model discrimination

4.1 Basic method

The objective of this work is to make the robot select an appropriate controller by itself to achieve higher degree autonomous operation under changes of operating conditions or current dynamics, by monitoring its dynamics continuously. Fig. 2 depicts the proposed control system. Several controllers to cope with each situation which can take place frequently through the ordinary operation, are prepared previously to realize a robust control system.

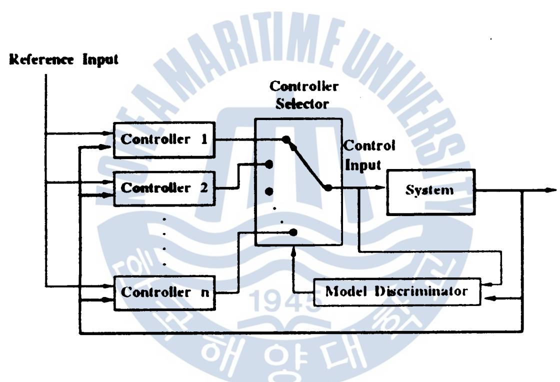

Fig. 2 The proposed adaptive control system

4.2 On-line model discrimination

One of important things to realize in the proposed control system above is how to discriminate robot′s current situation in real time. We considered a way comparing the output of simulators with the output of a real system to discriminate current situation.

4.2.1 Design of simulators

At first, three situations which can arise frequently through the ordinary navigation experiment are considered : moving successfully while keeping balance on the ground, being lifted-up from the ground, and engaging in a collision state.

(a) Design of a simulator for the situation moving while keeping balance on the ground (Simulator 1)

One dimensional model [1] for the inverted pendulum robot on a plane is given as

$$\dot{X} = AX + Bu \qquad (1)$$

where,

$$A = \begin{pmatrix} 0 & 1 & 0 \\ a_1 & a_3 & a_5 \\ a_2 & a_4 & a_6 \end{pmatrix}, \quad B = \begin{pmatrix} 0 \\ b_1 \\ b_2 \end{pmatrix}, \quad X = [\, x_1 \;\; x_2 \;\; x_3]^T$$

State variable x_1 and x_2, respectively, are the inclination angle and its angular velocity of the body and x_3 is the wheel′s rotation angular velocity. The equation (1) represents an unstable system, and it can not be applicable for simulator directly, since the calculated value diverges due to initial conditions or modeling errors. To solve such a problem, a state observer is incorporated.

In the real system, using a gyro sensor to measure posture, the drift error of the gyro sensor can not be neglected. Therefore, the system is augmented with a new state variable as the drift

$$x_4 = constant \qquad (2)$$

Considering that the inclination angular velocity of the body and the wheel′s rotation angular velocity, respectively, are measured with a gyro sensor and rotary encoder the state observer used for the simulator is given as

$$\dot{\widehat{X_a}} = A_a \widehat{X_a} + B_a u + G_a (y - C_a \widehat{X_a}) \qquad (3)$$

where,

$$A_a = \begin{pmatrix} A & 0 \\ 0 & 0 \end{pmatrix}, B_a = \begin{pmatrix} B \\ 0 \end{pmatrix}, C_a = \begin{pmatrix} 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}, G_a = \begin{pmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \\ g_{31} & g_{32} \\ g_{41} & g_{42} \end{pmatrix}, \quad \widehat{X_a} = [\, \widehat{X}^T \quad \widehat{x_4} \,]^T$$

$\widehat{X_a}$: estimated state vector

G_a : gain matrix which is decided appropriately to have suitable response

C_a : output matrix

(b) Design of a simulator for the situation being lifted off the ground (Simulator 2)

When the robot is lifted off the ground, the input current of the DC motor does not affect the posture of the robot. Hence, a model of the robot can be represented as

$$\dot{\omega} = -\frac{1}{T}\omega + \frac{k_m}{T}u \tag{4}$$

where, T and k_m, respectively, are the time constant and the steady state gain of this system, and ω is the wheel's rotation angular velocity.

Equation (4) can be used directly as a simulator because it is stable and its time constant is small.

(c) Design of a simulator for the situation engaged in a collision state (Simulator 3)

When the inverted pendulum robot collides with an object in the environment, its dynamics depend on the material of the object or the colliding state. Hence, we consider a method using the kinematics of the robot while colliding to detect collision.

When the robot is controlled to move straight and collides with the front wall, the mevement of the robot falls down slowly while keeping balance, i.e., the wheel rotates backward slowly, probably because of the control algorithm for posture keeping. This is known through the experiments. Fig. 3 shows the inverted pendulum robot after collision with the front wall. Let the inclination angle of the body be ψ, the rotational angle of wheel be θ, the distance from the center of wheel shaft to contact point with obstacle be d and the radius of wheel be r respectively.

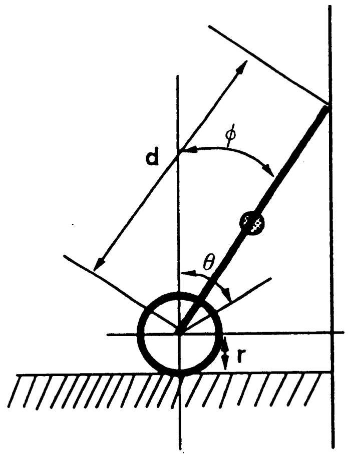

Fig. 3 The inverted pendulum robot in the collision mode

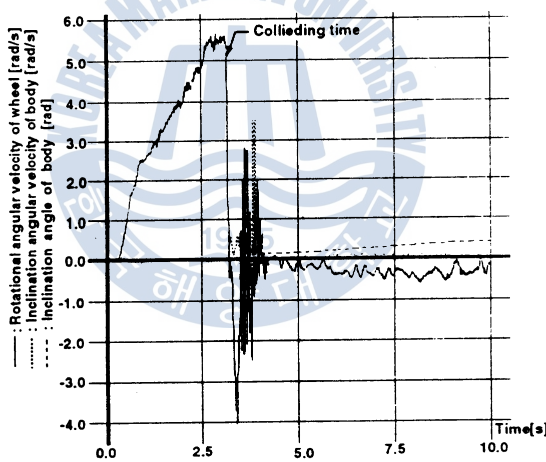

Fig. 4 Motion of the inverted pendulum robot after collision with the wall

Fig. 4 shows a variation of posture and velocity of the robot which collided with the front obstacle.

The kinematic equation (5) can be obtained from Fig. 3 and Fig. 4.

$$\theta = -\frac{d}{r}\sin\psi \tag{5}$$

Differentiating equation (5), $\dot{\theta}$ is given as

$$\dot{\theta} = -\frac{d}{r}\cos\psi\dot{\psi} \tag{6}$$

By observing the calculated value from equation (6) and the measured value of the encoder sensor, the colliding state of the robot can be detected.

4.2.2 Discrimination of three states

To discriminate each state of the robot, the outputs of encoder and gyro sensor are compared with the values calculated by the three simulators. However, This is not easy because of the noise contained in sensory data. So the moving average of the absolute value of the difference of measured value and simulated data are taken. The delay caused by the moving average duration is decided not to seriously affect robot control.

5. Implementation and experimental results

5.1 Determination of parameters

The effectiveness of the proposed algorithm was tested on Yamabico Kurara. Fig. 5 shows the proposed adaptive locomotion control system. In the experiment, the coefficient matrices A, B were calculated by using the parameters of Yamabico Kurara.

The gain matrix G_a of the state observer was determined through trial and error so that its response could be acceptable.

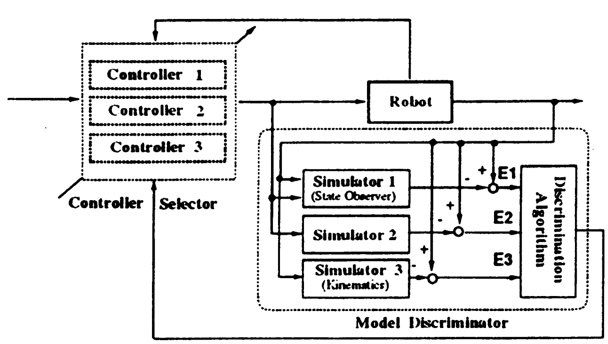

Fig. 5 Locomotion control system for the inverted pendulum type mobile robot

Eventually A, B, G_a were given as:

$$A=\begin{pmatrix} 0 & 1 & 0 \\ 38.23 & -0.085 & 0.121 \\ -57.76 & 0.347 & -0.56 \end{pmatrix},\ B=\begin{pmatrix} 0 \\ -13.7 \\ 56.06 \end{pmatrix},\ G_a=\begin{pmatrix} 50.0 & 0.0 \\ 100.0 & 0.0 \\ 0.7738 & 30.0 \\ -0.099 & 0.0 \end{pmatrix}$$

In equation (4), T and k_m were given 0.025, 23.3 from step response experiments, respectively.

By using the parameters, both measured and estimated wheel rotational angular velocity were compared, when the robot keeping its balance on the ground was lifted-up. The results are shown in Fig. 6, 7 where, M_1 and M_2 represent the moving averaged values of absolute difference for inverted posture controlling and lifted-up status respectively.

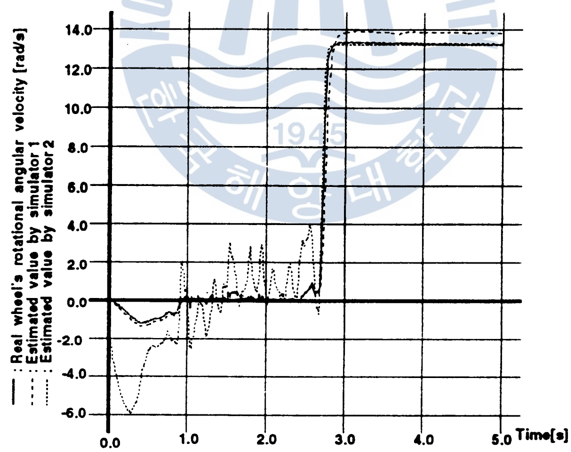

Fig. 6 Measured and estimated values of the wheel's rotational angular velocity when lift-up

We also observed M_1 and M_2 when the robot was put back on the ground from the lifted up state. The result is shown in Fig. 8. From these experiments, we could easily choose a threshold to discriminate these states.

In the collision experiment, the real angular velocity of the wheels and the calculated value from equation (6) is shown in Fig. 9. Thresholds were determined through these experiments.

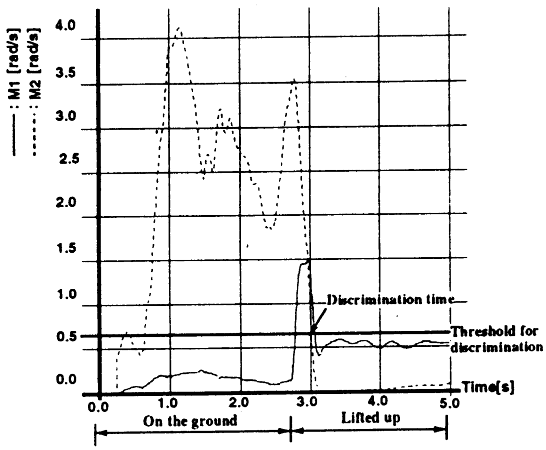

Fig. 7 Moving average of the estimation errors when lift-up

5.2 Implementation of adaptive control

The locomotion control system is designed to stop revolution of its wheel and to save dead reckoning data when robot is lifted up. Oppositely, when the robot is put upon the ground from being lifted up, it is made to wait for instruction from the master controller while keeping balancing control mode after reinitializing the parameters for balancing control. In case of collision, we made the robot detecting collision and part from obstacle while keeping its balance. Also, the control system is made to inform the master controller of the change of situations above.

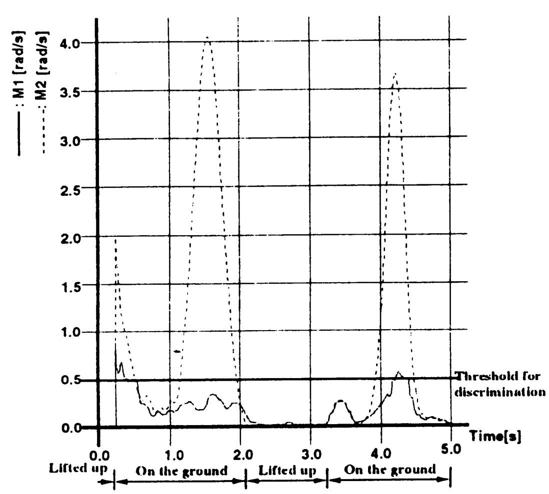

Fig. 8 Moving average of the estimation errors when put down

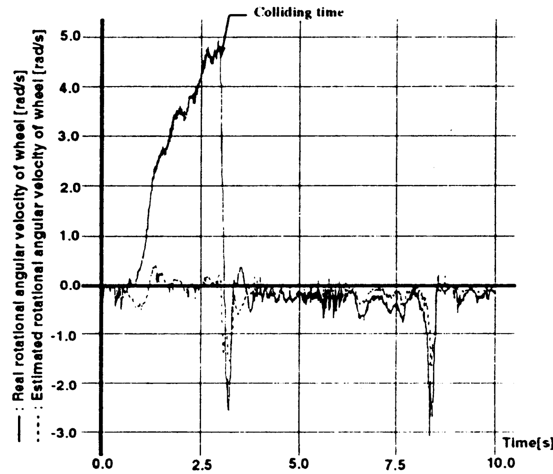

Fig. 9 Measured and estimated values of wheel's rotational angular velocity in collision state

5. 3 Experiments of adaptive control

In this section, experiments of posture control in the presense of changing operating conditions were carried out. Fig. 10 shows the results when an operator picked up the robot and put it on the ground. A dashed line shows the result of model discrimination, and 0, 1 means "on the ground state" and "lifted up state" of the robot, respectively. Fig. 11 shows the experimental results of collision. It can be seen that the robot discriminates collision at time A, rising the body to up-right posture at interval B and part from obstacle at interval C.

5. 4 Integrated indoor navigation of Yamabico Kurara

We integrated a robust indoor navigation system which include the proposed algorithm to cope with the changes of operating conditions. The intelligent Robot laboratory at University of Tsukuba was used as the experimental environment. In the experiments, even when an unexpected thin obstacle was put on the planned path, which is difficult to detect using by ultrasonic sensors, the robot detected the collision by itself and could cope with it. So the robot succeeded to navigate itself to the goal point while keeping its balance in spite of collision. An experimental scene is shown in Fig. 12.

6. Conclusion

In this paper, we proposed a robust control system of an inverted pendulum robot with the ability to select autonomously its control mode to correspond with operating conditions and dynamics. The control system was implemented on "Yamabico Kurara", and indoor navigation experiments were carried out. The experimental results demonstrated that "Yamabico Kurara" can have improved adaptability in a real world navigation.

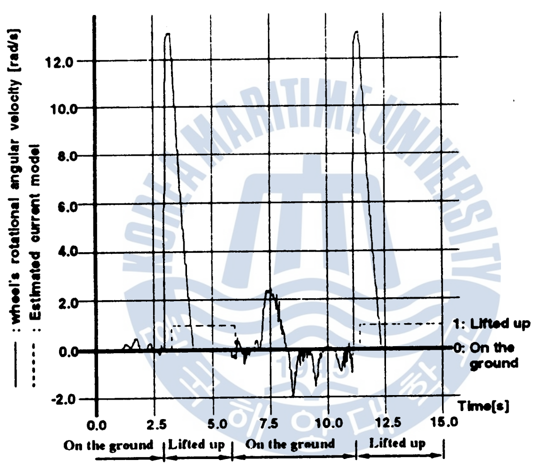

Fig. 10 A discrimination results of lift up

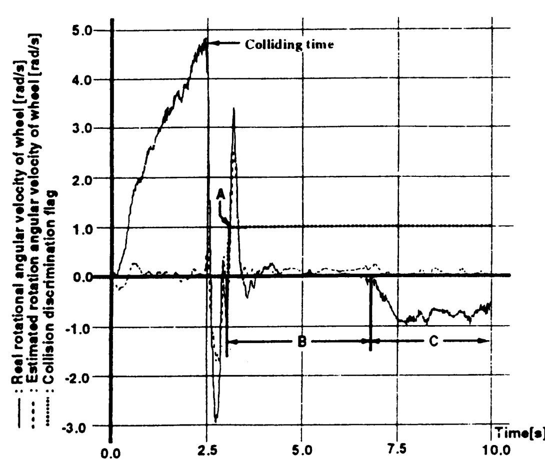

Fig. 11 A discrimination result of collision

Fig. 12 An experimental scene of indoor navigation

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