Development of an Autonomous Two-Wheeled Vehicle Robot

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Abstract. This paper describes a development of an autonomous two-wheeled vehicle robot. The model of the two-wheeled vehicle using steering control is derived. The control systems are designed by linear quadratic regulator and linear quadratic integral method. Stabilization is achieved by measuring roll angle and roll rate and controlling the steering torque. The experimental results and simulation results show stable running control of the two-wheeled vehicle robot and coincident with each other. The approach is validated through these results.

Introduction

Unmanned motorcycles or two-wheeled vehicles are inherently unstable nonlinear systems. Those properties strongly depend on travel velocity and friction between tires and load surface which makes the design of a stabilizing controller for such unmanned vehicles particularly challenging. Ruijs and Pacejka were probably the first to stabilize a motorcycle by feedback control. Getz and Marsden developed a controller that used both steering angle and forward speed to control riderless bicycles. Chidzonga and Eitelberg investigated the possibility of stabilizing a bicycle at rest by controlling the velocity when the front wheel is steered at a fixed angle. Miyagishi et al. used a proportional-derivative controller to control the roll angle of an unmanned motorcycle. Iuchi, Niki and Murakami presented MIMO two-degree-of-freedom control scheme, using both steering angle and center-of-gravity lateral shifting in order to keep a bicycle upright. Yi et al. presented a trajectory tracking and balancing control algorithm for an autonomous motorcycle. Weir and Sharp showed that motorcycle steering is achieved mainly through steering torque, while body-induced shift of the center of gravity is secondary. In this paper the controller design is based on Linear Quadratic Integrator controller. The approach is validated through simulations and experiments of straight running and curving running of the two-wheeled vehicle robot.
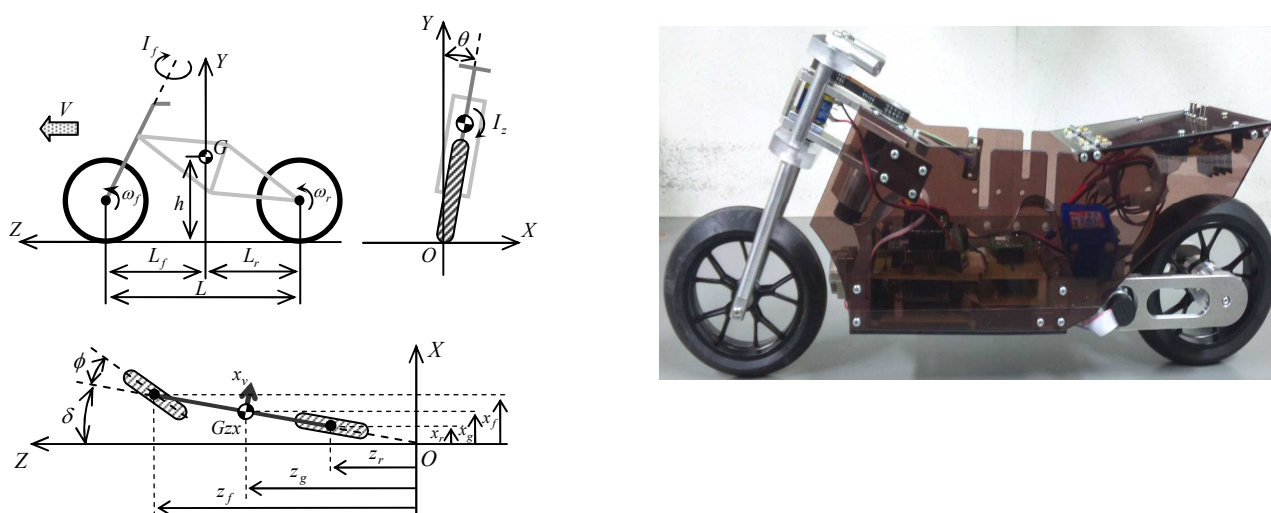

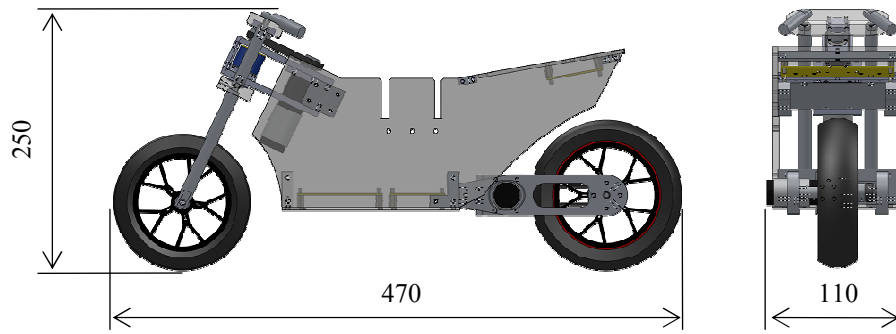Fig. 1. Overview of the two-wheeled vehicle robot

Fig. 2. Experimental prototype two-wheeled mobile robot

Two-wheeled vehicle robot

The experimental prototype robot with total length 470mm, hight 250mm, width 110mm, weight 2333g and maximum speed 3.2 m/sec is shown in Fig. 2. SH7144F microprocessor was installed on the robot and received roll angle, encoder outputs of steering angle and rear wheel rotation angle. Roll rate was measured using a vibrating ring gyroscope (Silicon Sensing Systems, CRS03-02).

Dynamic modeling

In order to design the controller, a dynamic model of the two-wheeled robot was derived under the following assumptions.

1. The body rotational angle δ around Y axis is small.
2. The steering angle ϕ and the tilt angle of the body θ are small.
3. Forward velocity is constant or changing slowly.
4. The center of gravity shifting of the robot is small when the steering angle changed.
5. The steering control is speed control system based on motor driver.

Under these assumptions, using the symbols defined as shown in Fig. 2, the following roll and steering equations are obtained;

$$\left(I_z + mh^2\right)\ddot{\theta} = mgh\theta - \frac{V}{L}\left\{mh\left(L_r + L_f\right)\frac{V}{L} + I_f\omega_f + I_r\omega_r\right\}\phi - \left(\frac{V}{L}mhL_r + I_f\omega_f\right)\dot{\phi} \tag{1}$$

$$\ddot{\phi} + \alpha\dot{\phi} + \beta\phi = \gamma u \tag{2}$$

And linearized roll and steering state space equations, state vector and output equation are obtained:

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{3}$$

$$y(t) = Cx(t) + Du(t) \tag{4}$$

where

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix}, \ B = \begin{bmatrix} 0 \\ 0 \\ b_3 \\ b_4 \end{bmatrix}, \ C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \ D = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \ x(t) = \begin{bmatrix} \theta \\ \phi \\ \dot{\theta} \\ \dot{\phi} \end{bmatrix},$$

$$\begin{cases} a = I_z + mh^2 \\ b = mgh \\ c = \frac{V}{L}\left\{mh\left(L_r + L_f\right)\frac{V}{L} + I_f\omega_f + I_r\omega_r\right\} \\ d = \frac{V}{L}mhL_r + I_f\omega_f \end{cases}$$

$$a_{31} = \frac{b}{a}, \qquad a_{32} = \frac{c}{a}, \qquad a_{33} = 0, \qquad a_{34} = \frac{d}{a}, \qquad b_3 = 0$$

$$a_{41} = 0, \qquad a_{42} = -\beta, \qquad a_{43} = 0, \qquad a_{44} = -\alpha, \qquad b_4 = \gamma$$

Properties of the two-wheeled robot were estimated either through direct measurements, e.g. physical dimensions and centers of mass; or by Computer Aided Design (Solidworks^{TM}) models based on measurements, e.g. calculation of moments of inertia. The parameters of the steering part were experimentally identified as shown in Fig. 3. Very little plant uncertainty was observed.

Controller design

In several control designs there is a wealth of experience and knowledge that dictates in many situations what sort of compensator dynamics yield good performance from the point of view of the controls engineer. For example, a washout circuit may be required, or it may be necessary to augment some feed forward channels with integrators to obtain a steady-state error of exactly zero. The control system structures used in classical aircraft design also give good robustness properties. That is, they perform well even if there are disturbances or uncertainties in the system. Our approach to tracker design allows controller dynamics of any desired structure, and then determines the control gains that minimize a quadratic PI over that structure. A dynamic compensator of prescribed structure may be incorporated into the system description as follows. Consider a state variable model of the plant given by Equations (3) and (4). We begin by considering a familiar design problem, the design of a controller to enable the tracking of a step reference input with zero steady-state error. The tracking error e is defined as

$$e = y - r \tag{5}$$

Taking the time derivative yields
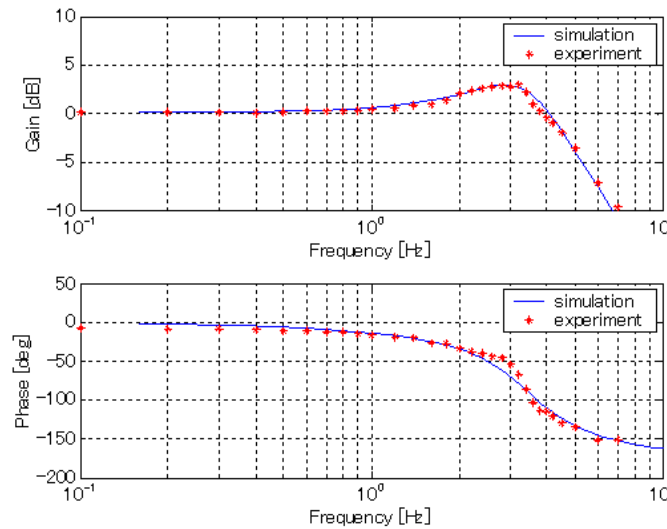
$$\frac{d}{dt}e(t) = C\dot{x}(t) \tag{6}$$
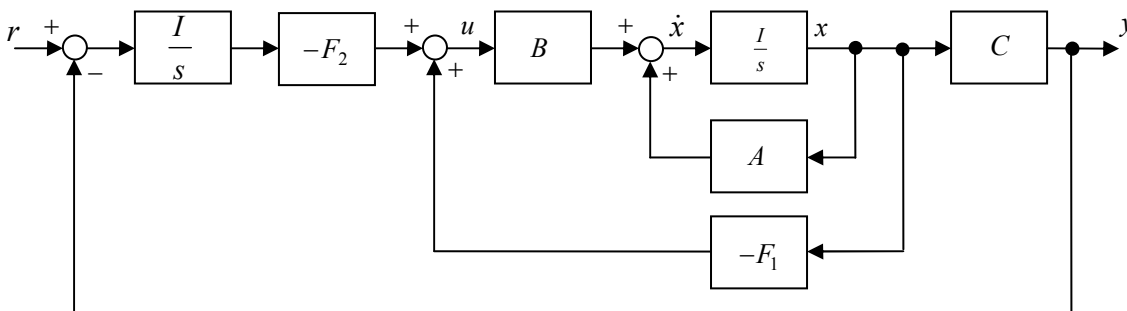

Fig. 3. Frequency response of the steering part

Fig. 4. Block Diagram of LQI

These dynamics and output equations may be written in augmented form as

$$\frac{d}{dt}\begin{bmatrix}\dot{x}(t)\\e(t)\end{bmatrix}=\begin{bmatrix}A & 0\\C & 0\end{bmatrix}\begin{bmatrix}\dot{x}(t)\\e(t)\end{bmatrix}+\begin{bmatrix}B\\0\end{bmatrix}\dot{u}(t) \tag{7}$$

If the system is controllable, we find a feedback of the form

$$\dot{u}(t)=-F_1\dot{x}(t)-F_2 e(t) \tag{8}$$

such that Eq. (7) is stable. This implies that the tracking error e is stable; thus we will have achieved the objective of asymptotic tracking with zero steady-state error. The control input, found by integrating Eq. (8), is

$$u(t)=-F_1 x(t)-F_2\int_0^t e(t)dt \tag{9}$$

The corresponding block diagram is shown in Fig. 5. We see that the compensator includes an internal model of the reference step input.

Table 1 Nominal value of the system

Nomenctature	Value	Unit
m	2.33	[kg]
h	0.096	[m]
L	0.360	[m]
L_f	0.195	[m]
L_r	0.165	[m]
R_f	0.058	[m]
R_r	0.064	[m]
I_z	7.35×10^{-3}	[kgm^2]
I_h	2.45×10^{-4}	[kgm^2]
I_f	2.51×10^{-4}	[kgm^2]
I_r	5.32×10^{-4}	[kgm^2]
k_m	0.017	[Nm/A]
R_m	9.72	[Ω]
n	19	[-]
g	9.8	[m/s^2]
α	17	[-]
β	-5	[-]
γ	19	[-]

Results and discussion

Straight running results. After repeating the design using several different R and Q, the weighting parameters are decided on $R=5$, $Q=diag[3000 \ \ 1 \ \ 10 \ \ 1 \ \ 20000]$. With this R and Q the control matrix was $K_1=[117.1678 \ \ -28.1724 \ \ 10.5698 \ \ -2.5429]$, $K_2=[141.414]$.

Figure 5 shows the results of simulations and experiments based on the designed controller with the sampling time 0.01[sec], the running speed 1.5[m/sec] and the reference body roll angle and steering angle are zero. It can be seen that the controller stabilizes the robot close to the vertical position. The good agreement between simulated and actual results is evident.

Curving running results. Figure 6 shows the results of simulations and experiments of the curving behavior of the robot with same conditions of straight running case. After 3 sec 10 [deg] step of the desired roll angle was changed. During all these tests the robot remained stable. Small fluctuations, in the range of -0.008436-+0.008436[rad/sec] about the zero roll rate angle, are most probably due to the fact that the sensor sets the dead zone for the drift of the sensor. However, simulated results and experimental results are almost agreement each other.
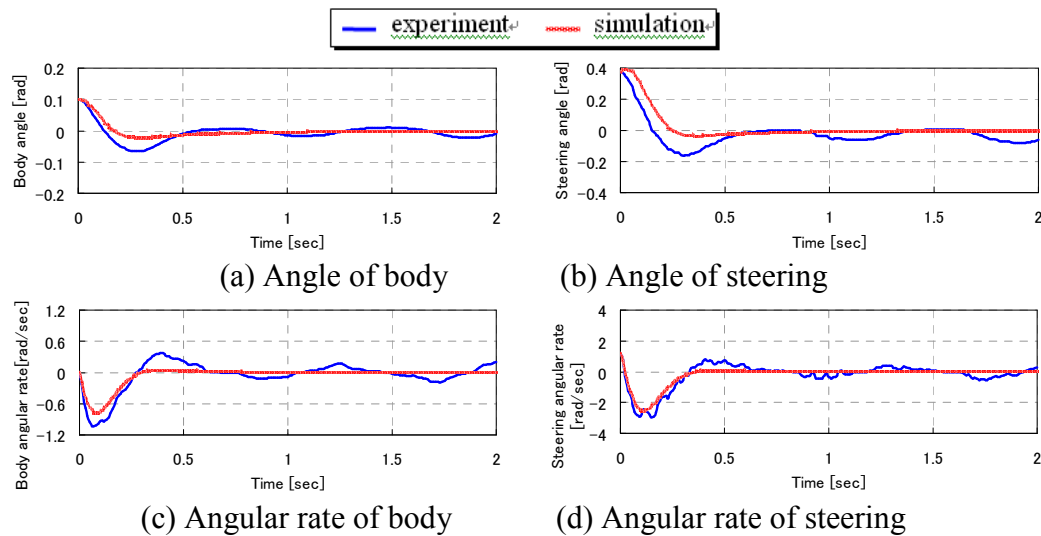
(a) Angle of body   (b) Angle of steering

(c) Angular rate of body   (d) Angular rate of steering

Fig. 5. Comparison of simulation and experiment results of straight running of the robot

(a) Angle of body   (b) Angle of steering

(c) Angular rate of body   (d) Angular rate of steering
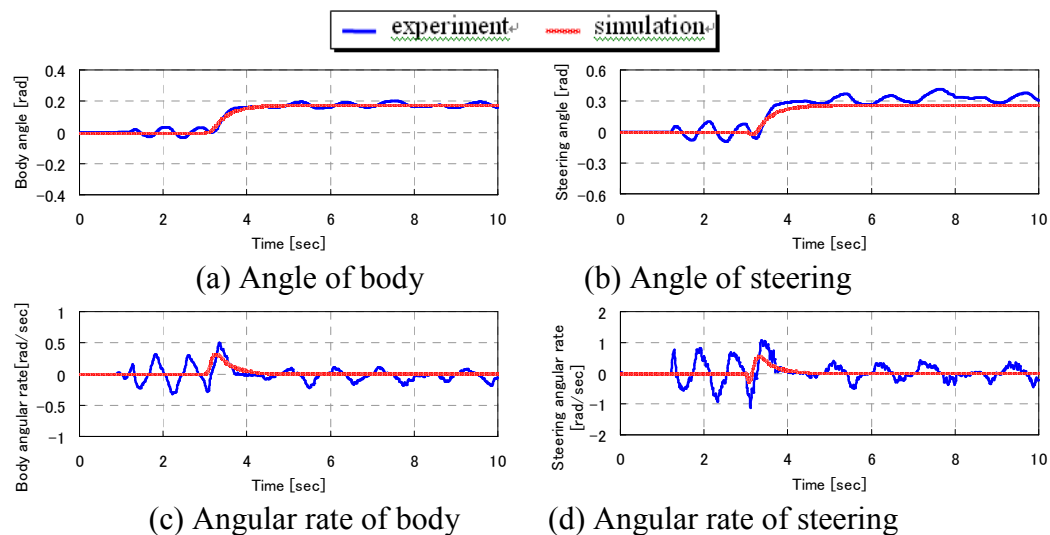
Fig. 6. Comparison of simulation and experiment results of curving behavior of the robot

Conclusions

A LQI controller that stabilizes an unmanned two-wheeled vehicle robot was developed and validated this controller was implemented on an experimental two-wheeled vehicle robot that was successfully autonomously operated on an carpet surface.

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