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STABILIZATION OF A SEGWAY TYPE MOBILE ROBOT

K.G.S. Darshana[1], A.W.C.D. Annasiwatta[1], D.H. S. Maithripala[2] and S.D. Pathirana[1]

[1]*Department of Production Engineering, Faculty of Engineering, University of Peradeniya.*
[2]*Department of Mechanical Engineering, Faculty of Engineering, University of Peradeniya.*

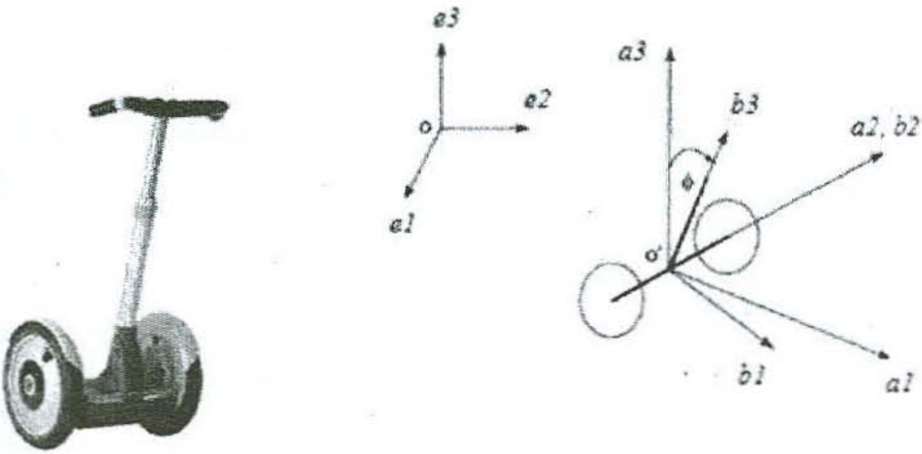
Introduction

The Segway is a commercially available human transport system that was unveiled in the year 2001. Such vehicles may also find applications in high maneuverable wheel chairs and rescue robots. Many results on maneuvering an inverted pendulum type mobile vehicle in an upright stable configuration can be found in the robotics literatures. The system is an under-actuated, non-holonomic system with high nonlinearities. The desired behavior is inherently unstable.

All existing controllers are based on linearized models. The first ever published results on stabilizing an inverted pendulum type mobile vehicle uses a Linear Quadratic Regulation (LQR) controller based on a linearized model that only considers tilt and wheel dynamics. In this study we develop a nonlinear energy shaping controller that is based on an inverted pendulum on a cart (IPC) approximation of the system. The controller implementation only requires that we measure the tilt, tilt rate and the wheel angular velocities. The only parameter that needs to be estimated is the entire mass of the system. We use a complete nonlinear model that considers the translational, tilt, yaw, wheel and DC motor dynamics with control voltage saturation to simulate the performance of the controller. Only wheel in-plane dynamics are neglected. The DC motors are assumed to behave ideally. Back-clash and friction in the geared drive are also neglected.

Mathematical Modeling

A schematic of the Segway is shown in Figure 1(b). We begin by picking a suitable set of coordinates by assigning frames as shown in Figure 1(b). Frame b is fixed on the body of the Segway with the origin O' coinciding with the midpoint of the wheel axis. The point O' has co-ordinates $[x\ y\ r]$ with respect to the earth fixed co-ordinate system e. A frame c is chosen such that it is parallel to b and is fixed on the vehicle with its origin coinciding with the center of mass G of the vehicle assumed to lie along the $b3 = c3$ axis. The angle between $b3$ and $a3$, the tilt angle, is ϕ and the angle between $a1$ and $e1$, the yaw angle, is θ. Let α_L and α_R be the counter-clockwise angle of rotation of the left and right wheel, respectively. The inertia tensor of the vehicle in the c frame is $I = \text{diag}\ [I1, I2, I3]$. We will neglect the in-plane inertia of each wheel and assume that the wheels remain upright. Two DC motors are directly coupled to the wheels. Each motor is assumed to behave identically. R_a is the armature resistance, L_a is the armature inductance, k_T is the torque constant, nd k_b is the back EMF constant of the motors.



(a) The Segway

(b) A schematic of the Segway

Figure 1: The Segway

In what follows we have used Euler-Lagrange equations to describe the motion of the body and Lagrange-D'Alembert's equations to describe the non-holonomic dynamics of the wheels.

The total kinetic energy and potential energy of the body is *KE* and *PE*, respectively. Thus the Lagrangian of the system is given by $L = KE - PE$.

Euler – Lagrange equations are:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) = \frac{\partial L}{\partial q_i} + f_i \ \ for\ q_i$$

$$= x, y, \emptyset, \theta \qquad (1)$$

The wheel torques are generated by DC motors, with dynamics,

$$L_a \frac{di}{dt} + R_a i + k_b \dot{\alpha} = e\,, \qquad (2)$$

Where *e* the control voltages applied to DC motors. Then the motor torques are given by,

$$T = k_T i \qquad (3)$$

The entire state space of the system is of fourteen dimensions. The only dynamics that are neglected in this model are the wheel in-plane dynamics. The objective of this paper is to develop controls motor voltages such that the vehicle can be maneuvered in an upright stable configuration.

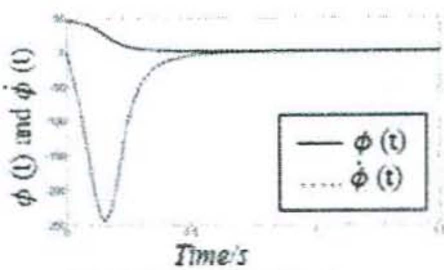
Stabilizing Controller

The primary control objective is to maneuver the vehicle in an upright stable configuration. The objective of this section is to find a stabilizing controls *e* such that $\emptyset \equiv 0$ is at least a locally asymptotically stable relative equilibrium with a large region of attraction. Controller is derived based on the IPC approximation and Stabilizing Controller is:

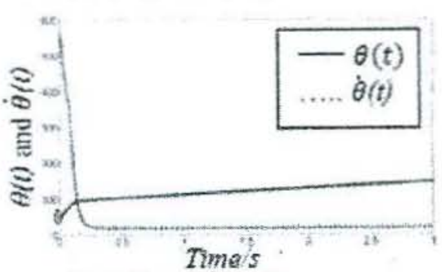
$$u = (m + M)g \tan\emptyset + \alpha \tan\emptyset + k_a \dot{\emptyset} \cos\emptyset \qquad (4)$$

Simulation Results

Simulation results correspond to parameters of a test vehicle (already assembled) where $M = 3.8$ kg, $I = I2 = 6.25 \times 10^{-3}$ kgm^2, $I1 = I3 = 3.82 \times 10^{-3}$ kgm^2, $L = 0.08$m, $I_w = 0.1 \times 10^{-3}$ kgm^2, $M_w = 0.01$ kg, $r = 0.1$m, $l = 0.15$m, $L_a = 1{\times}10^{-3}$H, $R_a = 2$Ohms, $k_T = 0.32$Nm/A and $k_b = 0.1$ V/radS^{-1}. The controller parameters were chosen as $\alpha = 20$ and $k_d = 3$. Figure 2 shows the simulation results corresponding to the initial condition (0, 0, 0, 0, 45°, 0, 0, 45°, 10, 0, 0, 0, 0, 0, 0) with $u_T = 0$. The controller (4) performs quite well even in the presence of large yaw rate.



(a) ϕ (t) and $\dot{\phi}$ (t) Vs t



(b) $\theta(t)$ and $\dot{\theta}(t)$ Vs t F

Figure 2: Simulation results of the Segway dynamics with the control (13)

Discussion

The system is non-holonomic in nature and is highly unstable. Thus the modeling and stabilization problems are extremely challenging. The implementation of the stabilizing control algorithm will require precision angular rate measurements.

Conclusion

The nonlinear energy shaping controller that is presented in equation (4) gives reasonably accurate performance. The simulation results also show robustness of the controller.

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