Equations Of Motion Of a Wheeled Inverted Pendulum

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The equations derived in [1] for the motion of two-wheeled inverted pendulum robot are:

$$3(m_c + m_s)\ddot{x} - m_s d cos\phi\ddot{\phi} + m_s d sin\phi(\dot{\phi}^2 + \dot{\psi}^2) = -\frac{\alpha_3 + \beta_3}{R} \tag{1}$$

$$\left\{(3L^2 + 1/2R^2)m_c + m_s d^2 sin^2\phi + I_2\right\}\ddot{\psi} + m_s d^2 sin\phi cos\phi\dot{\psi}\dot{\phi} = \frac{L}{R}(\alpha_3 - \beta_3) \tag{2}$$

$$m_s d cos\phi\ddot{x} + (-m_s d^2 - I_3)\ddot{\phi} + m_s d^2 sin\phi cos\phi\dot{\phi}^2 + m_s g d sin\phi = \alpha_3 + \beta_3 \tag{3}$$

where,
$\dot{x}$ is the heading speed of the robot
ϕ is the rotation of the C.G. about n_3-directional
ψ is the heading angle (angle between n_1 and the world frame)
α_3 is the torque of the left wheel
β_3 is the torque of the right wheel
m_c is the mass of the wheel
m_s is the mass of the body
d is the distance between wheel axis to C.G.
R is the radius of the wheel
L is the half distance between wheels
I_2 is the n_2-directional rotational inertia of the body
I_3 is the n_3-directional rotational inertia of the body
n_2 is the unit vector pointing vertically upwards
n_3 is the unit vector pointing from the left wheel to the right wheel

The equations that we had derived in our earlier report [2] did not include the rotation about the vertical axis of the robot. One of the equations above represent that motion. We will try to first match the equations we had derived with the equations listed above as a sanity check. Then we will write down the thrid equation using the variables that we had used in our earlier report. Then we will attempt to derive the equation using Newton-Euler method. Equations from our earlier report are listed here:

$$[(m+M)r+I_w/r+\eta^2 I_m/r]\ddot{x}+(mrlcos\theta-\eta^2 I_m)\ddot{\theta}=K_f u-\tau_f+F_{ext}rcos\theta+mrl\dot{\theta}^2 sin\theta \tag{4}$$

$$(mlcos\theta-\eta^2 I_m/r)\ddot{x}+(ml^2+I+\eta^2 I_m)\ddot{\theta}=-K_f u+\tau_f+F_{ext}l+mglsin\theta \tag{5}$$

where,
m is the mass of the body
M is the mass of the wheels
r is the radius of the wheel
I_w is the inertia of the wheel
η is the gear ratio of the motor
I_m is the motor inertia
$\dot{x}$ is the heading speed
l is the distance between wheel axis and the C.G.
θ is the rotation of the C.G. about the wheel axis
K_f is the torque to current ratio of the motor
τ_f is the frictional torque on the wheels
F_{ext} is the external force being applied at the C.G. perpendicular to l
I is the inertia of the robot about the wheel axis

Using the symbols used in equations 4-5, we re-write the equations 1-3:

$$3(M+m)\ddot{x}-mlcos\theta\ddot{\theta}+mlsin\theta(\dot{\theta}^2+\dot{\psi}^2)=-\frac{K_f(u_1+u_2)}{r} \tag{6}$$

$$\left\{(3L^2+1/2r^2)M+ml^2sin^2\theta+I_2\right\}\ddot{\psi}+ml^2sin\theta cos\theta\dot{\psi}\dot{\theta}=\frac{L}{r}K_f(u_1-u_2) \tag{7}$$

$$mlcos\theta\ddot{x}+(-ml^2-I)\ddot{\theta}+ml^2sin\theta cos\theta\dot{\theta}^2+mglsin\theta=K_f(u_1+u_2) \tag{8}$$

where, we have retained the symbols for quantities that do not appear in equations 4-5 i.e. ψ and I_2 which represent the heading direction and the inertia about the vertical axis respectively.

In equations 6-8, we make the following observations:

(i) Equations 6 and 8 are the equivalents of the equations 4 and 5 respectively

(ii) The equations 6 and 8 ignore the effects of wheel inertia I_w, the motor inertia I_m, frictional torque τ_f at the wheel motor and the external force F_{ext}, all of which were considered in equations 4 and 5

(iii) The terms containing $\ddot{x}$ in equations 4 and 5 appear with opposite signs in equations 6 and 8

(iv) The term $mrlsin\theta\dot{\theta}^2$ of equation 4 appears as $mrlsin\theta(\dot{\theta}^2+\dot{\psi}^2)$ in equation 6

(v) Equation 4 does not contain the coefficient 3 with the $\ddot{x}$ term which appears in equation 6

(vi) Equation 5 does not contain the term $ml^2sin\theta cos\theta\dot{\theta}^2$ which appears in equation 8

Point number (iii) may be explained by assuming that the two derivations assumed x increases in different directions. Point number (iv) may be explained by the fact that equations 4 and 5 assume constant heading direction i.e. $\dot{\psi} = 0$ But the last two points are not easy to explain. An interesting fact regarding point regarding (v) is that the paper [1] changes the term from $3(m_c + m_s)$ in the original equation that we cited aboce to $3m_c + m_s$ in the later equations of the same paper. It appears that the latter expression is more accurate and basically $3m_c$ represents the mass of three wheels of equal mass, one of which is a supporting wheel. The paper discusses supporting wheels at length, so it won't be surprise. That solves the mystery of the second last point. What remains now is to discuss the very last point. Since we see that there is a typo done in the earlier equation, we can expect this term to have a typo, in that it is missing a $\dot{\psi}$ term. If this was true we will safely assume that the reason this term isn't present in our earlier analysis (i.e. equations 4 and 5) is because we assumed constant heading direction i.e. $\dot{\psi} = 0$.

References

[1] Yeonhoon Kim, Soo Hyun Kim, and Yoon Keun Kwak. Dynamic analysis of a nonholonomic two-wheeled inverted pendulum robot. *Journal of Intelligent and Robotic Systems*, 44(1):25–46, 2005.

[2] Munzir Zafar, Can Erdogan, and Mike Stilman. Towards stable balancing. Technical report, Georgia Institute of Technology. Center for Robotics and Intelligent Machines, 2013.