Optimized Whole-body Motion Control for Wheeled Humanoid Robots

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Abstract

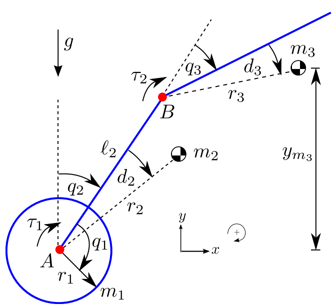
In this paper, the whole-body motion control of a dynamically-stable two-wheeled humanoid robot is investigated. With feedback linearization as a control law cooperating with a stochastic optimization technique called particle swarm optimization (PSO) to search for an optimal set of certain unknown parameters, an optimal robot motion can be realized according to a pre-fined performance index. The main contribution of this work is our first success on implementing the proposed control strategy on the actual physical system, Golem Krang, a novel two-wheeled humanoid robot developed at Georgia Tech. The experiments are demonstrated by two primitive motions, standing from the ground and deceleration.

Dynamics Model

The dynamics model of the robot is derived by Lagrangian mechanics as a two-wheeled planar double inverted pendulum resulted in the equation of the form

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{V}(\mathbf{q},\dot{\mathbf{q}}) = \tau, \qquad (1)$$

where $\mathbf{q} = [q_1, q_2, q_3]^T$ and $\tau = [\tau_1, 0, \tau_2]^T$.



Control

Let $q_a = q_1 + q_2$. Differentiate two CoM equations twice, we obtain the following equations :

$$w_1\ddot{q}_1 + w_2\ddot{q}_2 + w_3\ddot{q}_3 + v_4 = \ddot{y}_{m_3} \qquad (2)$$
$$w_4\ddot{q}_1 + w_5\ddot{q}_2 + w_6\ddot{q}_3 + v_5 = \ddot{q}_a \qquad (3)$$

Augment them into Eq. 1, we get

$$\left[\begin{array}{ccc|cc} & & & -1 & 0 \\ & \mathbf{M}(\mathbf{q}) & & 0 & 0 \\ & & & 0 & -1 \\ \hline w_1 & w_2 & w_3 & 0 & 0 \\ w_4 & w_5 & w_6 & 0 & 0 \end{array}\right] \left[\begin{array}{c} \\ \ddot{\mathbf{q}} \\ \\ \hline \tau_1 \\ \tau_2 \end{array}\right] = \left[\begin{array}{c} \\ \mathbf{V}(\mathbf{q},\dot{\mathbf{q}}) \\ \\ \hline \ddot{y}_{m_3} - v_4 \\ \ddot{q}_a - v_5 \end{array}\right] \qquad (4)$$

The control law is formulated by the inversion of the above mass matrix. $\ddot{y}_{m_3}$ and $\ddot{q}_a$ can be linearized by

$$\ddot{y}_{m_3} = -k_1(y_{m_3} - y^d_{m_3}) - k_2\dot{y}_{m_3} \qquad (5)$$
$$\ddot{q}_a = k_3 x^r_{cm} + k_4\dot{x}^r_{cm} + k_5 x^a_{cm} + k_6\dot{x}^a_{cm} \qquad (6)$$

where $k_i, i \in 1,2,..,6$ are control gains. y_{m_3} is the vertical position of the upper body CoM relative to the wheel axis. x^r_{cm} is the relative CoM of the entire body horizontally to the wheel. x^a_{cm} is the horizontal absolute CoM of the entire body.

PSO

PSO is a stochastic optimization technique inspired by social interaction which does not rely on gradient information but rather estimates the search direction through interactions with neighboring particles. We use PSO to search for the robot trajectory that minimizes the maximum wheel displacement (D_{p-p}) and motor inputs over a broad space of gains and reference as needed by Eq. 5 and 6.

The cost is defined as

$$\text{cost} = D_{p-p} + \int_0^T (R_1\tau_1^2 + R_2\tau_2^2)\,dt \qquad (7)$$

where $D_{p-p} = \max(q_a) - \min(q_a)$. R_1 and R_2 are scalar weight.

Implementation

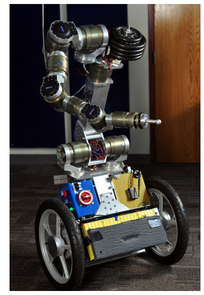
Simulation of PSO including joint position/velocity constraints was done in MATLAB to generate the control parameters and then they were tested on the robot.

Torque cannot be applied directly to the waist motors due to nonlinearity of harmonic drives. Therefore, a PD tracking control with gravity compensation was designed

$$\text{Motor input} = -k_p(q_3 - q_{3_s}) - k_v(\dot{q}_3 - \dot{q}_{3_s}) + k_g m_3 g r_3 \sin(q_2 + q_3 + d_3)$$

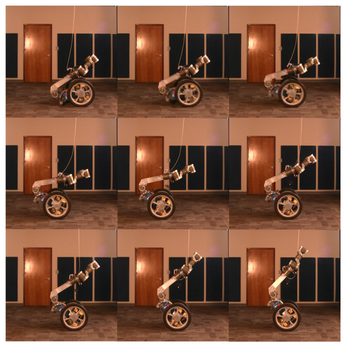
where k_p, k_v, and k_g are control gains. q_{3_s} and $\dot{q}_{3_s}$ are pre-computed trajectories of the waist motors obtained from simulation. For the wheel motors, torque command was normally used.

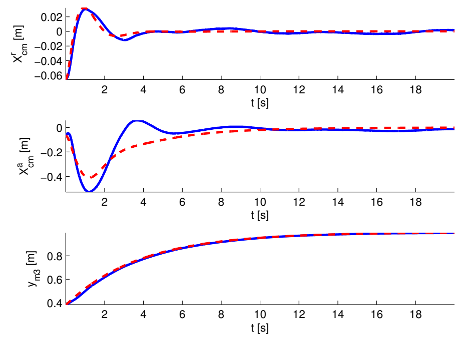
Golem Krang



Standing up with less space

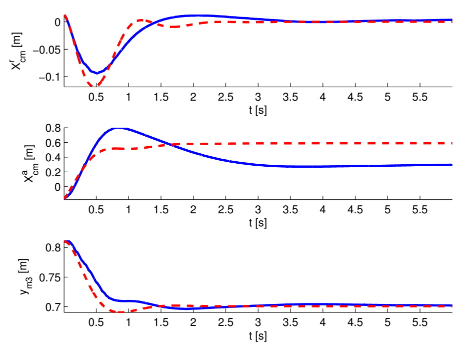
PSO chose k_1 to k_6. The target height was set as $y^d_{m_3} = 1.0$ [m]. The robot required 0.62 [m] to stand up to full height. Note that blue (solid) and red (dash) are of the actual robot and simulation, respectively.

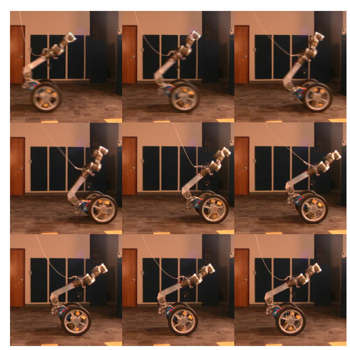




Deceleration by minimizing stopping distance

PSO chose k_1 to k_6 as well as $y^d_{m_3}$, except for k_5 which was set to zero. R_2 was also set to zero. The robot lifted its torso down in order to stop within 1.05 [m].





Deceleration by minimizing stopping distance and waist input

PSO chose k_1 to k_6 as well as $y^d_{m_3}$, except for k_5 which was set to zero. The robot lifted its torso up in order to stop within 1.17 [m] and with less torso input.