

Optimal Leg Stiffness and Gait for a Bipedal Robot with Parallel Elasticity



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Motivation

- Humans: Elasticity in muskokeslatal system enhances locomotion efficiency
- What is the optimal stiffness for a walking robot?
- How does elasticity change gait?
- How does choice of cost function affect gait?

Modeling

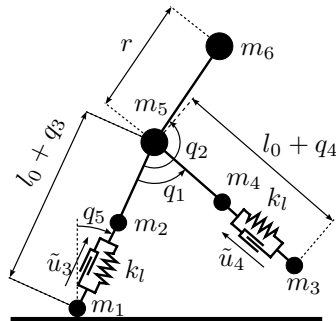
- Biped: two legs, torso; point masses at feet, leg, hip, torso
- Actuators are massless, frictionless and backdriveable.

- Impact: inelastic and instantaneous

⇒ Hybrid model

- Linear springs in parallel to leg actuators
- Spring force adds to actuator force
- Effective input:

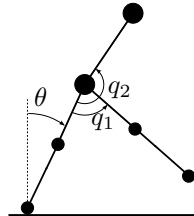
$$u_{3,4} = \tilde{u}_{3,4} - k_l q_{3,4}$$



Methods

- Gait Planning using concept of Hybrid Zero Dynamics [1]
Main idea/gait hypothesis:

- ▶ Point on body (e.g. hip) with absolute angle θ monotonically increasing over step
- ▶ Desired joint angles are functions of $\theta(t)$
- ▶ Use bezier polynomials with coefficients α



- Optimization of both bezier coefficients α (=gait) and leg elasticity k_l *simultaneously*

- Different cost functionals considered for optimization:

- ▶ Electrical work

$$J_1 = \frac{1}{mgL_s} \int_{t=0}^{t_s} \|\mathbf{u}(\alpha, k_l)\|_2^2 dt$$

- ▶ Mechanical work

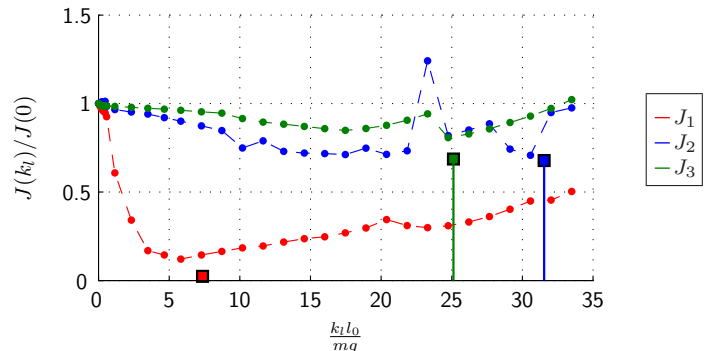
$$J_2 = \frac{1}{mgL_s} \int_{t=0}^{t_s} \|\dot{\mathbf{q}}(\alpha)^T \mathbf{B} \mathbf{u}(\alpha, k_l)\|_1 dt$$

- ▶ Positive mechanical work

$$J_3 = \frac{1}{mgL_s} \int_{t=0}^{t_s} [\dot{\mathbf{q}}(\alpha)^T \mathbf{B} \mathbf{u}(\alpha, k_l)]^+ dt$$

$$[x]^+ = 0 \text{ for } x \leq 0 \text{ and } [x]^+ = x \text{ for } x > 0$$

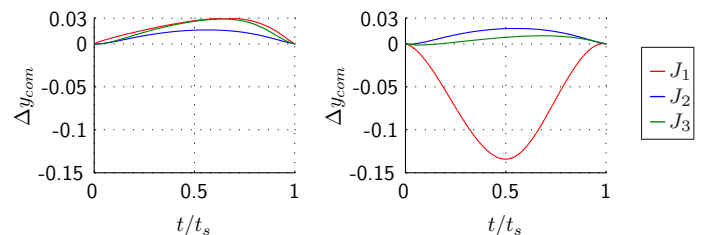
Optimization of k_l



- dot markers: optimization with fixed stiffness
- square markers: optimization with variable stiffness

Simulation Results

- Zero leg stiffness: inverted pendulum like vertical motion of center of mass (left figure)
- Optimized stiffness (right figure):
 - ▶ Cost function 2 & 3 remain similar
 - ▶ Cost function 1: Motion similar to spring mass system



Conclusions

- Optimal leg stiffness depends on cost function
- Simultaneous optimization of stiffness and gait is advantageous, leads locally to lower costs
- Cost function 1 exhibits energy storage and release mechanism, more promising for generalization

Future Work

- Investigate effect of varying speed on leg stiffness
- Include double support phase with non-zero duration
- Use approach on biped with knees and feet

Selected References

- [1] E. Westervelt et al., IEEE Trans. Autom. Control, 2003
- [2] M. Scheint, Technical Report TR-2008-05, TU München, 2008