Feedforward Optimal Control with Stabilizing Optimal Trajectory Tracking to Emulate Human Motor Control

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Abstract This paper proposes a human-inspired walking controller consisting of a feedforward optimal term and a feedback stabilizing term. The feedforward term is the optimal control input as calculated from the dynamics using trajectory optimization via direct collocation. The feedforward optimal control is analogous to walking muscle synergies in humans, which are the learned muscle contraction patterns that humans use during walking. The feedback term involves tracking the deviation from the optimal joint trajectories with a PD controller, and this term can be seen as approximating the stability which comes from co-contraction and natural stiffness and damping in human joints. This hybrid controller mimics human motor control in the hopes of obtaining some of the robustness of human walking, and it aims to offset the disadvantages of using feedforward or feedback alone. Feedback mitigates the sensitivity of feedforward to minor perturbations. Feedforward combats the vulnerability of feedback to sensor noise and allows lower feedback gains to be used, since the motion of the biped is no longer entirely reliant on the feedback term. Preliminary results using this controller in the simulation of a five-link biped are presented, in which the proposed controller is compared to a feedback linearizing controller when subjected to an impulse perturbation.

Keywords bipedal walking, feedforward optimal control, five-link biped, human-inspired

1. Introduction

There is a need to advance bipedal walking. Bipedal robots have many applications including in-home assistive care, disaster relief, and as assistive devices such as lower-limb exoskeletons for rehabilitation or permanent assistance. Studying bipedal walking and finding parallels between robot walking and human walking is particularly useful for designing assistive devices, like exoskeletons and prostheses, and developing their control strategies.

This paper is not the first to suggest a hybrid controller with a feedforward term to facilitate the rhythmic motion of walking and a feedback term to enhance stability. Huang et al [1] generated optimal ZMP walking trajectories and included the optimal motion (most likely the control input) in the feedforward term; used ZMP control, body posture control, and landing time control in the feedback term; and applied their controller to a 26-DOF humanoid robot. Hong et al [2] employed ZMP walking with a pole-zero cancellation by series approximation controller in the feedforward term and an LQR controller in the feedback term in simulation. Alibeji et al [3] calculated the optimal control for a lower-limb exoskeleton using a subject-specific dynamic model, and muscle synergies were extracted from this control input and included in an adaptive feedforward controller with stabilizing feedback. Kuo [4] conducted a more general study with a simple pendulum which showed that including both feedforward and feedback terms could compensate for disturbances and sensor noise.

Control strategies in bipedal walking are still being researched, since bipedal walking is inherently unstable from a controls perspective and since bipedal robots do not yet exhibit the stability and robustness of human walking. This gap between robot and human walking is due to differences in control methods and in physiology; this paper works toward closing the gap in control strategies. Optimal walking trajectories are generated for a five-link bipedal robot, and the biped is subjected to a perturbation in simulation, where the optimal control is in the feedforward term and simple PD joint trajectory tracking is in the feedback term. Comparisons are made between the proposed controller, which will be referred to as human-inspired and a feedback linearizing controller. Unlike the feedback in Huang et al [1], the feedback here is meant only to emulate the robustness of human walking from joint stiffness and damping to minor disturbances. Future work will involve a high-level controller to treat recovery behaviors.

2. Methods

The five-link biped has relative joint angles as defined in Figure 1. Its equation of motion is given in Equation 1, where J is the Jacobian of the hip joint and δF is an impulse perturbation. The biped is simulated for ten steps, with the impulse delivered at 0.2 seconds during the first step. The impulse is approximated with a sharp Gaussian curve centered at the impulse time, and the foot impact dynamics are handled as an inelastic collision as in [5].

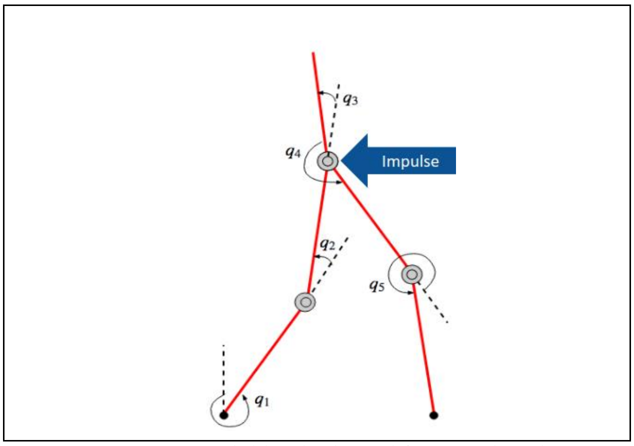

Figure 1. Five-link biped with joint definitions and impulse

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = Bu + J^T\delta F \qquad (1)$$

The trajectory optimization is performed in Julia using JuMP to model the direct collocation problem and using IPOPT as the solver. The optimal joint and control trajectories are converted to functions using cubic spline interpolation and fed as arguments to the forward simulation. The optimal control is used as the feedforward term, and the optimal joint angles and velocities are used for trajectory tracking in the feedback term.

The proposed human-inspired (*HI*) controller is compared to feedback linearization (*FL*) because *FL* is widely accepted and because *FL* was the inspiration for the proposed controller. In the absence of perturbations, the *FL* control input is identical to the optimal control input. Thus, the only difference between the two controllers is that the *HI* controller treats this optimal control input as feedforward; when tracking error is zero, both controllers achieve the optimal control input. Both controllers have the same actuator limits and PD gains in the simulation. The *HI* and *FL* control inputs are given in Equations 2 and 3, respectively, where matrix arguments are suppressed for space.

$$u = u_{opt} + K_p\left(q_{opt} - q\right) + K_d\left(\dot{q}_{opt} - \dot{q}\right) \qquad (2)$$

$$u = M\left(\ddot{q}_{opt} + K_d\left(\dot{q}_{opt} - \dot{q}\right) + K_p\left(q_{opt} - q\right)\right) + (C\dot{q} + G) \qquad (3)$$

3. Results and Discussion

The biped was simulated for ten steps under three conditions: solid lines are the true optimal trajectories, dashed lines are the perturbed *HI* trajectories, and sparse dotted lines are the perturbed *FL* trajectories. The resulting joint trajectories, q_1 through q_5, for three steps and an impulse magnitude of 10 *Ns* are given in Figure 2.

HI tracks for all ten steps with a slight time shift due to the disturbance. *FL* has a noticeably larger time shift and fails to track after the fourth step (not pictured).

4. Conclusion

The results show that *HI* is promising for rejecting perturbations, especially compared to *FL*. It would seem that including the optimal control explicitly as a feedforward term is more beneficial than having it implicit in feedback, as is the case with *FL* when tracking error is zero. This simulation did not look at rejection of sensor noise, but there are plans to inspect this on a physical system in future works.

References

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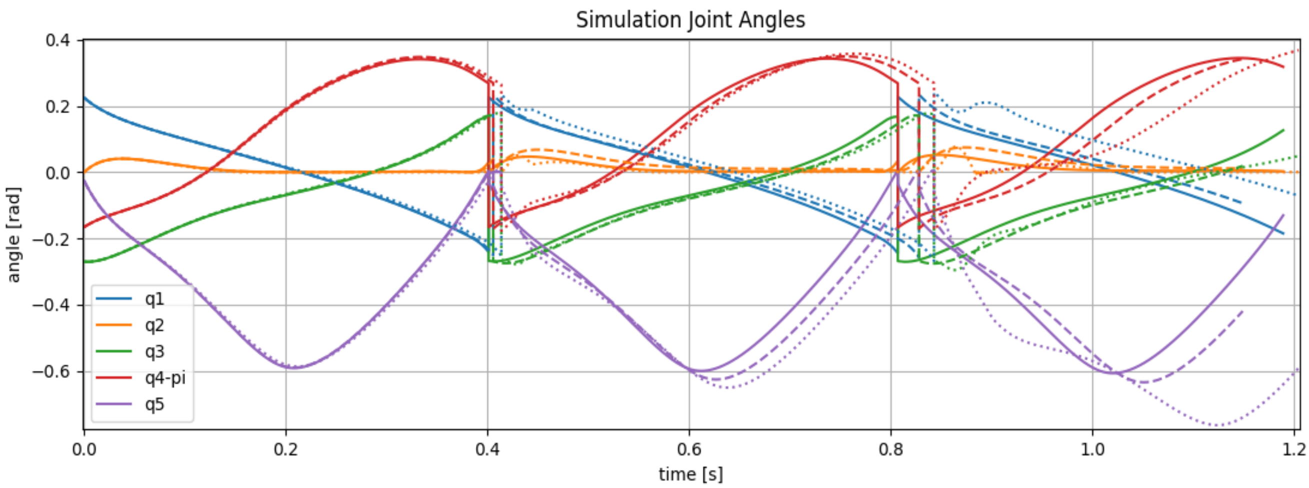

Figure 1. Joint trajectories for three steps (optimal - solid, perturbed HI - dashed, perturbed FL - dotted)