Dynamics and Control of Spring-Mass Robots with Compliant Legs

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Abstract

The objective of this study is to propose control strategies for legged robots to walk and run naturally like humans and animals. To achieve this goal, we use the spring-mass model for the legged robots to be able to create the same dynamics in the leg as humans and animals. In this way, understanding the natural dynamics of the system plays the central role and the strategy is to manipulate the dynamics of the system in the favor of final goals. To fully leverage the passive dynamics of the system in this study, the model is assumed to be passive except when the energy of the system needs to be managed.

The study starts with analyzing the dynamics of the bipedal spring-mass model for walking and understanding the available workspace of the system along with the different types of limit cycles that exist in each energy level. After that, based on the limitations and control authority that the bipedal spring-mass model provides for passive walking, a deadbeat control strategy is proposed to pinpoint the system to the desired states and it is shown that two steps are necessary and sufficient for the deadbeat control. The basin of attraction of the equilibrium points with this control policy shows the robustness of this strategy and the extension of the deadbeat control technique to various energy levels can handle walking on rough terrain and recovers the system in two steps. It turned out that the sensitivity of the system to the touch-down angle is a challenging part of implementing two-step deadbeat control on real robots. Therefore, unlike the deadbeat control technique that pinpoints the system to the desired states, four swing leg control policies based on time and based on the states of the system are proposed to gradually approaches the desired limit cycles. Since the convergence to the desired equilibrium gaits is gradual, the sensitivity of the control policies to external errors reduces. The large basins of attraction of these proposed control policies show that the system can be reliably controlled to the desired gaits after large perturbations. Furthermore, a time-based feed-forward control strategy for the stance phase of the bipedal spring-mass model is combined with the time-based swing leg control policy to stabilize the model and manages the energy of the system. The simulations show that time-based feed-forward technique is stable and can robustly manages the states and energy level of the system especially for spring-mass system with some damping in parallel to the spring. Finally, a flight phase control policy is proposed for spring-mass running robots through investigating birds' running experiments. In this control policy, three objective functions i) leg peak force, ii) axial impulse and iii) leg actuator work, all from passive stance phase, were considered to be regulated during running. It turned out that with a simple swing leg policy (constant leg angular acceleration), all the three objective functions can be nearly regulated at the same time, meaning that both goals of damage avoidance and energy efficiency can be fulfilled at once.

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