A Case for Spring-Mass Physics in Legged Robots

Jonathan Hurst, Dynamic Robotics Laboratory (http://mime.oregonstate.edu/research/drl/), Corvallis, Oregon

I. Introduction

We suggest that spring-mass physics is the foundation for legged machines that will achieve the agility, robustness, and energy economy we see from animal locomotion.

Utilizing spring-mass physics necessarily splits the passive dynamics of the mechanical system from the control. This is antithetical to the classical control idea of creating all desired behaviors through control, using actuators simply as an imperfect implementor of the desired behaviors; instead, the passive dynamics and the controller meet in the middle, both playing their own role as partners in generating the behavior.

II. Control Benefits

The bipedal spring-mass model describes walking and running gaits, as shown in Figure1, building on prior work by Geyer et al. [1], Salazar and Carbajal [4], and Rummel et al. [3], among others. The oval point cloud in the figure shows reachable states for walking gaits at *a fixed energy level*, meaning that no energy is gained or lost in this conservative model. Different energy levels caused by actuation or uneven ground would add a third dimension out of the page. The red points in the plot represent equilibrium gaits, where each stride is the same as the last, and red points at $\psi = 0$ represent symmetrical equilibrium gaits, where the first and last half of the stance forces are exactly mirrored. The red points extend to running and hopping, but non-equilibrium reachable states for running or hopping are not shown.

Simple controllers can enable continuous transitions across this state space of gaits, passing through the snapshots shown at the top of Figure 1, from hopping in place at the top left, to running, to grounded running, to walking with a flat force profile, to walking with a classic double-hump force profile, finally transitioning to a double-leg hopping gait at the far right (not shown). Further, this diverse state map of reachable states allows convenient handling of disturbances and unpredictable terrain. A disturbance simply places the system at a different place in the state map, and it is possible to generate control policies that are exponentially stable over a large basin of attraction.

III. Implementation Benefits

The benefits of spring-mass physics are only realized when a physical system generates the appropriate passive dynamics. (1) Appropriately tuned springs are more efficient in absorbing and releasing energy in a cyclic gait than any actuator; (2) they significantly amplify the power output of actuators for cyclic gaits; (3) springs handle unexpected ground impacts elegantly, and (4) eliminate most of the inelastic collision losses; and springs (5) eliminate the massive force spikes that occur during

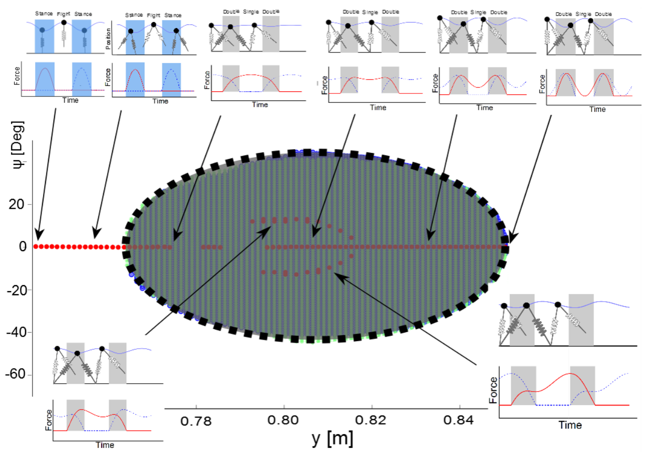

Fig. 1. This very simple model describes a continuum of gaits from hopping in place on alternative feet, through grounded running, walking, and hopping with paired feet.

ground impact with standard actuators. A spring-mass system is (6) not sensitive to impact uncertainties, such as touchdown timing errors, because the transition of force is gradual and the dynamics of the spring-mass system generally dominate whatever ground dynamics may exist. Mass-spring systems are inherently series-elastic, which means that (7) force control during stance is a natural capability[2]. Using force control, variations in animal leg stiffness or damping that have been reported in the biomechanics literature can be explained.

IV. Conclusion

Spring-mass machines can be built. They can be controlled. While there remains work to do, we suggest that design and control approaches based on spring-mass physics will be the foundation of future legged machines.

References

[1] Hartmut Geyer, Andrew Seyfarth, and Reinhard Blickhan. Compliant leg behaviour explains basic dynamics of walking and running. *Proceedings of the Royal Society B-Biological Sciences*, 273(1603):2861–2867, 2006.

[2] D. Koepl and J.W. Hurst. Impulse control for planar spring-mass running. *Journal of Intelligent and Robotic Systems*, 2013.

[3] J. Rummel, Y. Blum, and A. Seyfarth. Robust and efficient walking with spring-like legs. *Journal of Bioinspiration and Biomimetics*, 5, 2010.

[4] Harold Roberto Martinez Salazar and Juan Pablo Carbajal. Exploiting the passive dynamics of a compliant leg to develop gait transitions. *Physical Review E*, 83, 2011.