The Effect of Mass Distribution on Bipedal Robot Efficiency

Matt Haberland*, Hunter McClelland**, Sangbae Kim*, and Dennis Hong***
* Biomimetic Robotics Laboratory, MIT, Cambridge, Massachusetts, USA (mdhaber@mit.edu, sangbae@mit.edu)
** Department of Mechanical Engineering, Virginia Tech, Blacksburg, Virginia, USA (hgm@vt.edu)
*** Robotics and Mechanisms Lab, UCLA, Los Angeles, California, USA (dennishong@ucla.edu)

2 Desired Presentation Format
The preferred presentation format is a poster because we would like the opportunity to discuss the work in greater detail with smaller groups of conference participants.

3 Motivation and 4 State of the Art
Energy efficiency is among the properties of legged robots in greatest need of improvement [1] and is one of the key factors limiting the use of legs for autonomous system locomotion [2]. One of the major determinants of energy consumption in human walking stems from the step-to-step transition [3], which intuition and simple models suggest is highly influenced by mass distribution; e.g. reduced distal leg mass reduces the impact losses which must be replaced each stride [4]. Accordingly, many researchers have studied the extent to which mass distribution can affect the efficiency of robot models [5] [6] [7], biological bipeds [8] [9] [10] [11] [12], and biological quadrupeds [13] [14] [15]. However, the applicability of existing results to the design of new physical robots is limited because:
• conclusions from studies of biological systems may not be applicable to robots due to significant differences in gaits and relevant physics (e.g. of the actuators),
• conclusions from studies of particular systems are not necessarily applicable to other robots due to differences in design parameters and control strategies, and
• conclusions from studies of heavily simplified systems may not be applicable to physical robots due to important differences in the dynamics and the possibility that impact energy loss does not correlate with overall efficiency [16].

To address these shortcomings, we are studying the effect of added mass, such as batteries, control electronics, or payload, on robot efficiency, as measured by cost of transport. Using methods from [16], the results will be directly applicable to a wide variety of walking and running robot designs and control strategies in order to help individual robot designers improve their robot’s overall locomotion efficiency.

5 Our Approach
The results of this experiment will be applicable to a variety of practical robots that are well-modeled by the rigid body system depicted in Figure 1: a distributed-mass torso with a pair of two-segment distributed-mass legs. Therefore, robot designs to be tested will be randomly sampled from a design space, or population of robots of this architecture, as illustrated in Figure 2. Specifically, we will independently sample each of several dimensionless parameters that uniquely define the average walking speed and physical variables of such a robot. The Buckingham Pi theorem assures us that the nondimensionalized results will be valid for robots of any mass or geometric scale.

Figure 1: Architecture of the walking model used in this study: a five-link, kneed biped with a torso and point feet. The independent variable is the fraction k/H of the robot’s full height at which additional mass, representing batteries or payload, is added; the dependent variable is the optimal efficiency of limit cycle walking.

Figure 2: Graphical representation of many example robots sampled from the design space. Link width represents link mass; links are drawn such that the mass is equal to the product of link width squared, link length, and a density factor common to all designs. The center of each circle represents the center of mass of each link, and the circle radius corresponds with the link radius of gyration. The use of random sampling from the population allows us to make inferences directly relevant to a designer’s robot without knowledge of the particular design.
For each of many such robot designs, the test will consist of measuring the cost of transport of limit cycle walking under each of several levels of the independent variable: the location of an additional mass representing, for example, a battery. The cost of transport will be measured as the integral of the power consumed over the gait by all the actuators, calculated according to the standard steady-state electromechanical equations of a DC motor, normalized by the robot’s weight and distance traveled. As this metric depends not only on the robot design but the particular gait chosen, and as there is no standard gait or even control strategy common among robot designers, the gait will be chosen by trajectory optimization to minimize the cost of transport. This cost of transport of the resulting gait provides a bound against which designers can compare their own robots. Trajectory optimization will be performed using GPOPS-II [17] from guesses randomly generated from generous bounds on all time, state, and control variables. While the nonlinear programming algorithm used can only find local minima, we will repeat optimization from many such random guesses in attempt to provide a tight upper bound for the global optimum.

The results of testing a particular robot design will be the minimal cost of transport of walking at a particular speed. By statistically analyzing the results of many such tests with different robot designs, each with their own energetically-optimal gait, we can find trends applicable to all robots within the design space, and thus to all real robots well modeled as described.

6 Discussion

The methods described are new to the field, especially the use of Monte Carlo methods / statistics to make rigorous inferences about an entire class of realistic robots. These should be of interest to any researcher attempting to provide generally applicable answers to high-level robot design questions, but also to biologists hoping to provide answers to physiological questions via simulation. One question we would like to discuss with participants from all backgrounds is “to what questions from your field might this method be applied?” In particular, we would be interested in asking biologists about physiological studies which might be carried into the engineering domain using this method.

7 Travel Grant

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References