Extracting Principles from Biology for Application to Running Robots using Optimization

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1 Introduction

A traditional approach to designing hardware or control systems is to begin with a task to be accomplished, proceed to brainstorm possible solutions, and select from the options based on their relative merits. This approach discourages settling for preconceived, suboptimal solutions. In cases where millions of years of evolution appear to point toward a particular answer, we may be tempted to abandon this methodology and adopt the biological solution. It is precisely in these situations, however, that we must be most cautious of accepting the apparent answer. Evolution tends to improve survival, but not necessarily optimize performance of any one desired task. Therefore, we should attempt to extract only the principles relevant to the task of interest and measure them against other design candidates. I propose a framework for extracting biological principles using optimization and adapting them for application to robots.

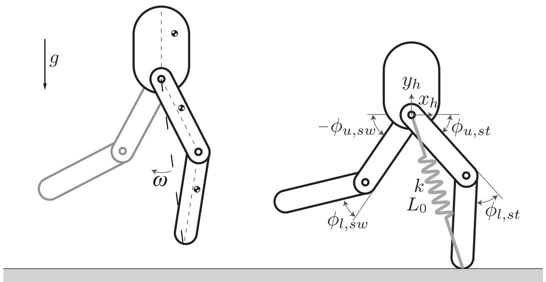

Figure 1: The Phides robot model is 2-dimensional (planar) and consists of five rigid bodies with distributed mass: a torso, two upper legs, and two lower legs. To match the Phides robot as it currently runs, I fix the rotation of the torso with respect to the world. This leaves the model with 6 degrees-of-freedom: the horizontal and vertical positions of the hip, the rotations of two hip joints, and the rotations of two knee joints. Torques, limited to 21.4 Nm to represent the actuator limitations of the robot, act at all four joints.

2 Method/Case Study

The general method is illustrated through a case study: isolating the effect of swing leg retraction on running energy efficiency.

2.1 Observe

Swing leg retraction is the behavior observed of humans and animals in which the airborne front leg rotates rearward prior to touchdown [1] [2] [3]. It is interesting that animals do not always simply position the foot and hold it, awaiting impact.

2.2 Hypothesize

It seems intuitive that the unexpected behavior of the swing leg might reduce the impact between the foot and the ground [4]. It is further hypothesized that if swing leg retraction is applied, then overall running efficiency will improve [5]. I wished to test this principal for its applicability to running machines.

2.3 Model

I modeled the running of the Phides robot [6] using the system of rigid bodies illustrated in Figure 1. I quantified swing leg retraction as the angular rate of the 'virtual leg' line connecting the hip to the point foot, and measured energetic efficiency using mechanical cost of transport [7], or the absolute work done over a stride normalized by robot weight and distance traveled.

2.4 Optimize

Constraining the retraction rate to each of several values within a range, the mechanical cost of transport of limit cycle running is minimized starting from 10 random seeds. Optimization was performed using GPOPS [8] (the license of which requires that [9] [10] [11] [12] [13] [14] [15] [16] [17] be explicitly cited). GPOPS robustly converged to different local minima limit cycles from these seeds, but the values of the mechanical cost of transport tended to cluster toward values presumed to be the global minima.

2.5 Analyze

The values of the minima exhibited a trend as retraction rate varied, as shown in Figure 2, which can be interpreted as the global sensitivity of the mechanical cost of transport with respect to the swing leg retraction rate.

2.6 Conclude

From this I conclude that for this running speed and these particular parameters, swing leg retraction can improve en-

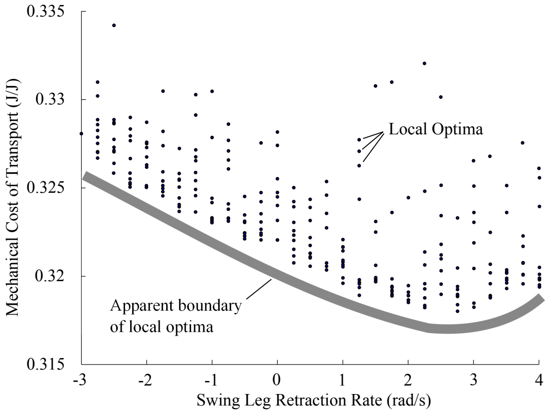

Figure 2: Each point represents the locally minimal mechanical cost of transport of an optimal limit cycle found by nonlinear programming from a random initial seed. For each swing leg retraction rate, the minimal mechanical costs of transport cluster towards what appears to be a lower bound. The resulting curve approximates the global lower bound, or the sensitivity, of the minimal mechanical cost of transport as a function of swing leg retraction rate.

ergetic efficiency to a certain extent, beyond which further swing leg retraction speed decreases energetic efficiency. By repeating a similar experiment for multiple running speeds and varied parameters, I generalized these results to a class of dynamic robots.

I do not attempt to use the results of optimization at face value or directly apply the quantitative results to a particular robot. I am interested in distilling notable ideas from observation that can be used as intuition and suggest directions of more detailed study. For instance, I do not claim that the retraction rate found to yield minimal mechanical cost of transport is 'best' for this particular robot, much less all robots. What I take away is the notion that swing leg retraction does indeed affect overall energetic efficiency, as hypothesized. However, I found that the dependence of this effect on speed and parameters is more complicated than expected. Even more surprising was that as retraction rate increased, so did impact losses, which was later explained but initially conflicted with intuition.

3 Future Case Studies

Using this framework, I will attempt to study such topics as the effects of:

- leg morphology on biped running speed and efficiency
- gait transitions on quadruped running efficiency
- spine flexibility on running speed and efficiency
- tails on quadruped maneuverability

From each study, I hope to distill information that can be added to our intuition and thus used in the robot controller or hardware design process.

4 Open questions

I would like to discuss the following questions at the conference:

- To what extent can we trust lower-dimensional dynamic models of running and walking for building our intuition?
- To what extent do answers of the form 'The effect of [this] on the 'optimal' value of [that]' answer the question 'What is the effect of [this] on [that]?'

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