Extracting Principle 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 pre-conceived, 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 optimize survivability of genes (ref) and not necessarily performance of any one desired task. Therefore, we should attempt to extract only the principles relevant to the task and measure them against other design candidates. I propose a framework for extracting biological principles using optimization and adapting them for application to robotics.

2 Case Study: The Effect of Swing Leg Retraction on Running Energy Efficiency

I motivate the general method with a case study.

Swing leg retraction is the behavior observed of humans and animals in which the extended front leg rotates rearward before the foot contacts the ground. We find it interesting that animals do not always position the foot and hold it, awaiting impact, as some early robots did [ref]. We hypothesize that this unexpected behavior reduces the impact between the foot and the ground, and further guess that if swing leg retraction is applied, then running efficiency will improve, and that this principal might be applied to machines.

To test this hypothesis, I modeled the running of the Phides robot using principles of rigid body dynamics as illustrated in Figure 2. I quantify swing leg retraction as the angular rate of the ‘virtual leg’ line connecting the hip to the point foot, and measure energetic efficiency using ‘mechanical cost of transport’, or the absolute work done over a stride normalized by robot weight and distance travelled.

Constraining the retraction rate to each of several values within a range, optimization is performed to minimize the mechanical cost of transport of limit cycle running from 10 random seeds. Optimization is performed using GPOPS (the

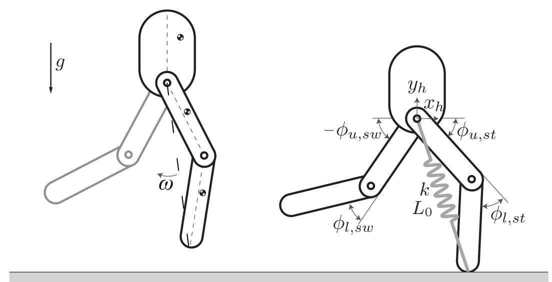

Figure 1: The Phides robot model is 2-dimensional (planar) and consists of five rigid bodies with distributed mass: a torso, two upper legs, and two lower legs. For this study, we fix the rotation of the torso with respect to the world to eliminate the need to control the torso orientation. This leaves the model with 6 degrees-of-freedom: the horizontal and veritcal 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.

license of which requires that [] be explicitly cited). GPOPS robustly converges to different local minima limit cycles from these seeds, but the values of the objective function, mechanical cost of transport, tend to cluster toward a value presumed to be the global minimum.

Furthermore, these values exhibit a trend as retraction rate varies, as shown in Figure 2, which can be interpreted as the global sensitivity of the mechanical cost of transport to the swing leg retraction rate. From this we can conclude that for this running speed and these particular parameters, swing leg retraction can improve energetic efficiency to a certain extent, beyond which further swing leg retraction speed decreases energetic efficiency. By repeating the experiment for multiple running speeds and varied parameters, or perhaps by allowing parameters to be chosen as decision variables of optimization, we can generalize these results to a class of dynamic robots.

3 Method

The method demonstrated above can be divided into six steps:

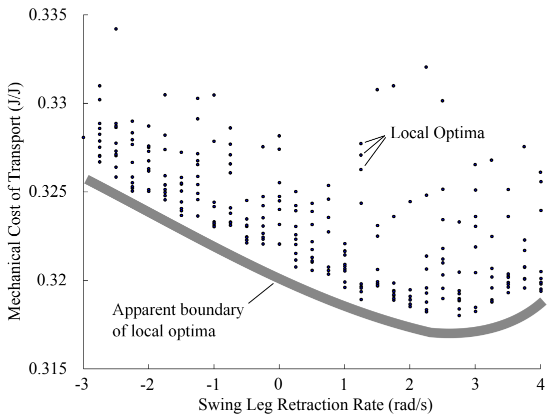

Figure 2: Each point represents the locally minimal mechanical cost of transport of an optimal limit cycle found by non-linear programming from a random initial seed. For each swing leg retraction rate, the minimal mechanical costs of transport cluster towards what appears to be a lower bound. The resulting curve approximates the global lower bound, or the sensitivity, of the minimal mechanical cost of transport as a functi5on of swing leg retraction rate.

1. Observe: Scientists and engineers look to nature for inspiration. This step relies on inate human curiosity and ability to recognize patterns.
2. Hypothesize: When we observe feature or pattern that we find interesting, we may attempt to explain them by making an educated guess of the form 'If [independent variable] [does this], then [dependent variable] [does that]'.
3. Model: To test the guess, we model the system in question using physical principles and determine quantitative measures of the independent and dependent variables. Our model must allow the independent variable to change and the dependent variable to be measured. It need not, however, allow the 'independent' variable to change truly independently of all other variables.
4. Optimize: Using the dynamics of our model and the value of the independent variable as constraints, we optimize for the extremal value of the dependent variable. I attempt to use GPOPS as a tool to query the inherent effect of the independent variable on the dependent variable because although the 'independent' variable does not change truly independently, the condition of optimality serves in place of experimental constants. In this respect, the method outlined here is a extension of the 'scientific method' taught in primary education.
5. Analyze: We study the results of the optimization, which tells us something about the effect of the independent variable on the extremal value of dependent variable. Visualization of the data, and especially the sensitivity of the optimal value of the dependent variable with respect ot the independent variable and other parameters, allows us to recognize trends.
6. Conclude:

4 Future Case Study

Using this framework, I will attempt to answer questions such as:

- The effect of leg morphology on running speed and efficiency
- The effect of gait transitions on quadrupedal running efficiency
- The effect of spine flexibility on running speed and efficiency
- The effect of the tail on quadruped maneuverability

From each study, I hope to isolate 'nuggets' of information that can be added to our intuition and thus used in the design process.

I don't 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 a 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, but never before directly tested. However, the magnitude of the effect, and in fact the general sensitivity of efficiency with respect to SLR rate, is complicated and speed and parameter dependent. This work should augment intuition that 'swing leg retraction reduces ground impact' with...

5 Open questions

I would like to discuss several questions with those

- Does this seem like an original and useful direction to pursue for my thesis?
- What existing work should I be aware of as I continue my studies?
- What questions do you have that might be studied within this construct?
- To what extent can we trust 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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References

[1] M. Guide, “The mathworks,” *Inc.*, *Natick*, *MA*, vol. 5, 1998.