Motor Selection Using Task Specifications and Thermal Limits

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I. Introduction

Choosing the appropriate motors for a legged robot poses challenges not typically faced by designers in other venues such as mechatronics or automation, principally due to the highly varied and fundamentally intermittent nature of a running, climbing, crawling machine's interactions with its environment. Currently, many designers rely heavily on empirical trial and error, with subsequent versions of a robot built primarily to test motor/gearbox iterations[1]. More rational approaches to motor sizing employ dynamical simulations of the robot in question [1], [4]. In this work we explore a still more principled approach to motor sizing, attempting to develop mathematically generated (i.e., formally guaranteed) guidelines while taking into account the interaction of motor dynamics and thermal behavior with the "task" assigned to the robot.

Robot motor and gearbox selection has traditionally been driven by industrial applications, in which a task typically consists of a known target trajectory [6] (eg. a robotic arm in an assembly line lifts and precisely maneuvers a specified part) accomplished by an amply-sized actuator. However, in the realm of mobile, legged robots, motor choice and leg trajectories can not be so neatly divorced. Severely constrained power density and the imperatives of highly dynamic locomotive performance [1] dictate that motors in legged robots be operated at or near their physical limits, inextricably coupling motor capabilities (and damage/failure conditions) to robot behavior. Hence, we address two coupled problems: the representation of a motor operating regime, and a model of the thermal consequences of that operational mode.

We dynamically generate a motor operating regime by simulating a task (in this paper, a vertical climb) which may be accomplished via very distinct joint trajectories at execution time depending on the motor and gearbox choices made at design time. A motor thermal model [9] evaluates the thermal effects of task achievement. This enables us to evaluate motors based both on their ability to accomplish a given task, but also incorporating some view of the quality of the performance they afford.

The motor selection methodology developed here is motivated by the experience of operating-point-based motor selection for X-RHex [3], and we believe our approach and results may prove useful for others addressing actuator choice for motors in legged robots. Specifically, coupling the electromechanical to the thermal models, we examine the mathematical consequences of intermittent motor use in a legged robot, and use some of the insights so developed to identify which subset of motor parameters are most pivotal in influencing intermittent motor performance.

[1]This design procedure was required for EduBot, RiSE, DynoClimber [2], and most recently X-RHex [3].

II. Problem Statement

A central challenge to rational motor selection is an appropriate representation of a robot's "task domain" which should result, roughly speaking, in a distribution over the actuator speed-torque plane characteristic of the intended operational regime. In this preliminary work we side-step any general resolution of that key issue by committing to the very specific task domain of vertical locomotion (both leaping and steady climbing) as follows.

We apply our coupled motor models to a scenario in which the actuator must lift a constant mass vertically against gravity, absent any friction. Note that we do not specify a time-parametrized trajectory; this leaves substantial freedom in how precisely the task is accomplished, spanning a range of design choices that we render as varied control policies in the following manner. The motor can either be running *continuously*, in which mode a constant voltage is applied to the motor terminals, or *intermittently*, wherein the motor switches between operation at a constant voltage and being disconnected from the system (in the latter case, it applies no force). The continuous operation mode can be thought of as a robot with wheels rolling up a pole, while the intermittent operation mode would be a legged robot that bounds or leaps upward. Within this very specific task domain, we characterize formally the manner in which legged robots (with intermittent loading requirements) pose a fundamentally different set of requirements for motor selection than do applications in which continuous power delivery is acceptable.

III. Results

A. Analytical results

We first consider, analytically, the simple, constrained scenario arising from introducing a fixed amount of mechanical energy in the shortest possible amount of time. We prove that a motor operating at a constant velocity introduces less (wasteful) thermal energy than does a motor operating intermittently (with such operations' requisite variation in velocity).[2] Smoothing actuator power output is intuitively beneficial; thermal energy emitted by the motor coil is proportional to the square of motor torque, while at a given speed, motor power output is linearly dependent on output torque. This result represents a *fundamental property* of motors that cannot be affected by changing the reduction ratio or control scheme.[3]

Conventionally, thermal effects have been accounted for primarily by heeding a manufacturer-specified continuously acceptable torque rating [8], [3], [1]. However, our mathematical result shows that analysis based upon continuous approximations is not sufficient in the context of legged robots due to the inherent penalty of intermittent operation. Moreover, it begins to suggest those motor characteristics which are most pivotal in achieving good intermittent performance.

B. Simulation results

While our analytical results preclude intermittent operation from being more efficient, specific morphological or task requirements often force us to use our motors in such a regime. Through exhaustive simulation of the Maxon Motors catalog [5], we are able to identify those motors which incur the smallest thermal "penalty" for intermittent operation.

Simulations of motors drawn from the catalog reveal dramatic differences in the thermal penalties associated with intermittent operation by otherwise similar motors. We propose a motor parameter feature set rooted in quantities which appear in our theoretical analysis as prominent components of motor thermal behavior. We expect that regression based upon such a feature set will provide several quantities which

[2] Our assumption is that, as is the case for a legged robot, intermittent operation is constrained morphologically (eg. ground contact occurs only periodically), yet within any given "on" period, we wish to maximize actuator output power and therefore apply constant (maximal) voltage to the motor terminals.

[3] "Control scheme" here refers to the policy or rule that controls the on/off switching schedule in intermittent operation.

accurately predict motor thermal performance. These quantities can be easily computed and used as heuristics to aid in motor selection without requiring a designer to rely on the full simulation procedure outlined here.

IV. Conclusion

We have outlined a principled approach (if not an algorithm) to tackle the coupled problems of motor and gearbox selection from both mechanical and thermal dynamic perspectives. In so doing, we introduce a novel concept of task specification and proceed by leveraging optimization, dynamic simulation, and analysis tools.

We achieve a broad-reaching analytical result demonstrating the cost of intermittent motor operation. Our result further justifies roboticists' previous work on the introduction of passive-elastic energy storage to improve average actuator power output [1], [7], and gives strong motivation to promote — through mechanical design — an approximately constant motor speed.

While the vertical climbing task presented here is kinematically restrictive, it generates motor trajectories across a broad range of regimes in the speed-torque operational plane. We are confident that the heuristics which predict strong intermittent climbing performance in this setting will similarly apply to intermittent behavior in other task domains as well. Even for applications with strikingly different requirements, we have outlined tools and techniques which can be used to determine the set of motor characteristics that play a similarly crucial role in affecting the execution quality of that task.

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