Pushing Robots to their Limits - Trajectory Optimization For Robots Using Heat Constraints

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***Abstract*—Humans often find it necessary to complete tasks outside their range of continuous energy expenditure. We are often required to execute tasks such as picking up heavy objects or jump much higher that pushes our muscles to their limits. These anaerobic movements are useful for short time limits as governed by our body. In this work, we aim to model a similar phenomenon in humanoids with electric motors. In standard trajectory optimization problems, we set hard torque constraints; however, as long as we are able to model the heat generation and dissipation, we can overcome these limits for short amounts of time in order to execute high-load tasks such as jumping higher than normal.**

I. Introduction

Due to recent advances in 3D printing and actuation technology, robots with electric motors have become more prevalent [1]. Research on these robots often involves solving trajectory optimization problems which include the physical actuation constraints (i.e. torque) of the robots. These constraints are usually specified by the manufacturer with the intent to ensure the long-term viability of the actuator. The torque output of electric motors, however, is truly only limited by the material properties of their windings; as long as care is taken to not reach a certain temperature threshold, we can go over the manufacturer's torque specifications for short amounts of time. For a legged robot, for example, one can imagine jumping higher than previously capable or using specific joints to compensate for a broken or degraded joint to create new gaits. Previous work has touched upon this idea, however, a proper framework was never developed to be used in a flexible, on-line manner [2]. By modeling the heat generation and dissipation in a trajectory optimization framework, we can create much more complex tasks. This idea can be thought of as analogous to anaerobic exercise in humans, in which humans use a different metabolic process that can only supply energy to muscles for a short amount of time.

II. Heat Generation Models for Brushless DC Motors

The bottom right image of Figure 1 shows a typical RPM vs. current curve. We can enter the short term regime on the right for a brief period and achieve much higher levels of current (and in effect, torque) output. As long as we return to the continuous operation region without overheating the motor winding, we can ensure the lifetime of the motor will not be significantly reduced. In order to do so, we use the two resister model from [2]. A trajectory optimization problem can then be formed with the discretized differential equation for heat transfer replacing the hard torque constraints. Although this framework is not capable of an MPC style controller for locomotion, we can currently create simple one off tasks such as higher hopping for simple hoppers and lifting loads with robot arms well outside the specifications of the manufacturer.

A. Initial Test Setup and Results

In order to verify how well the heat generation model tracks the trajectory optimization problem, we first created a simple motor setup with a custom motor controller board that allowed us to go above the current limits. The physical 1-DOF test setup included an EC-60 Maxon brushless DC motor with a weight enacting a torque on the motor shaft outside the specified torque limit. Finally, a trajectory optimization problem was solved using the framework mentioned in the previous section. The torque commands that the solver found were then sent to the motor controller. Figure 1 shows early results of tracking using a heat sensor attached to the windings of the motor compared to the predicted output of the trajectory optimization problem.

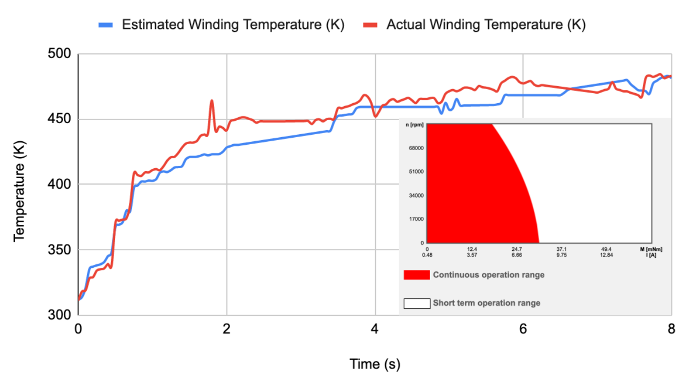

Fig. 1. [Main image]:Early Hardware test of actual winding temperature (red) vs. Temperature predicted by the trajectory optimization problem. [Bottom Right Image]: Typical RPM vs. current curve for a Maxon motor. We can move from continuous operation range (in red) to the short term operation range (white) for short amounts of time.

References

[1] F. Grimminger *et al.*, "An open torque-controlled modular robot architecture for legged locomotion research," *Arxiv*, 2019. [Online]. Available: https://arxiv.org/pdf/1910.00093.pdf

[2] J. Urata *et al.*, "Thermal control of electrical motors for high-power humanoid robots," in *IEEE/RSJ International Conference on Intelligent Robots and Systems (ICRA)*, Nice, France, 2008.