Pushing Robots to their Limits

Trajectory Optimization For Robots Uisng Heat Constraints

Paarth Shah, Ioannis Havoutis, Ludovic Righetti

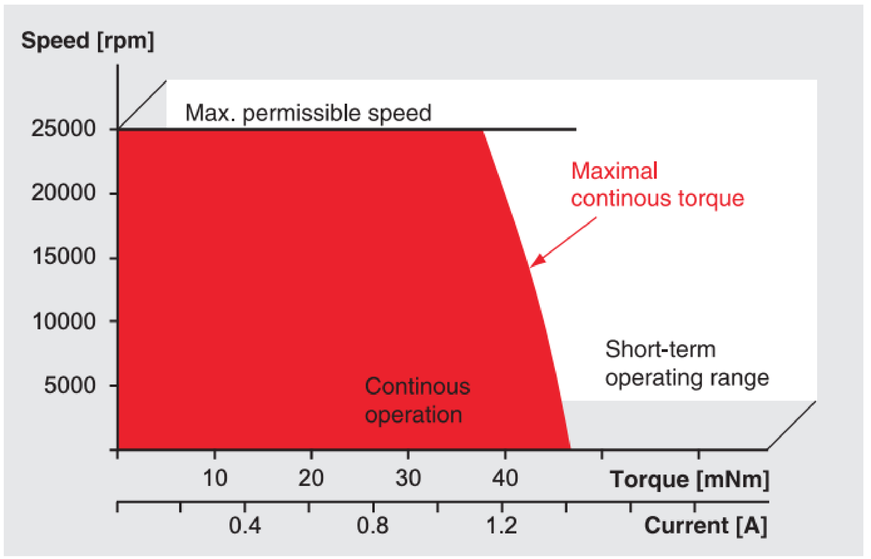
Motivation

- Humans often find it necessary to complete tasks that require a higher amount of energy than what they can do on a continual basis (e.g. picking up heavy objects)
- There has been an increase in the number of legged robots that use electric motors rather than hydraulics; these robots generally are torque constrained [1]
- We can use a trajectory optimization method using heat constraints matching physical limits of electric motors rather than hard torque constraints to mimic the anaerobic, high load movements of humans in legged robots

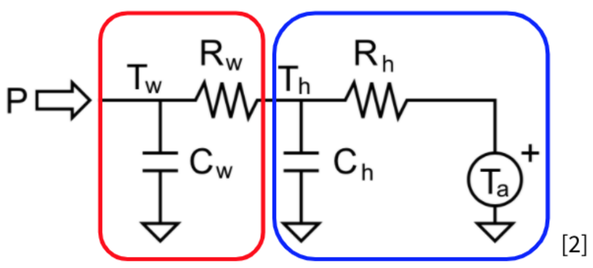
Figure: The ANYmal robot is a legged quadruped driven by electric motors.

Theory

- The torque output of electric motors is truly only constrained by the thermal limits of the windings
- If we can model the heat generation and dissipation of these motors and use these new thermal limits, we can get movements that are outside of the limits of the traditionally constrained optimization
- If we combine the heat dissipation and generation model with a robotics trajectory optimization framework [2], we can create much more free-form motions that adhere to the dynamics of the heat transfer allowing dynamic motions



Implementation



[2]

$$C_w \frac{dT_w}{dt} = P - \frac{T_w - T_h}{R_w}$$

$$C_h \frac{dT_h}{dt} = \frac{T_w - T_a}{R_h}$$

$P = Power\ Input$
$C_{w,h} = Thermal\ Capacitance$
$R_{w,h} = Thermal\ Resistance$
$T_{w_k} = Winding\ Temperature\ (Above\ T_a)$
$T_{h_k} = Housing\ Temperature\ (Above\ T_a)$
$T_a = Ambient\ Temperature$

Figure: Two resistor model used for heat generation and dissipation. Red outline indicates heat generated due to current, blue outline indicates heat loss from motor housing to surroundings (i.e. ambient temperature)

Heat Generation Model:

- Most motors don't have temperature sensors in the windings
- In order to account for this, we use the two resistor model proposed by Urata to generalize this framework to as many robots as possible [3]
- We measure the outside of the motor housing rather than the windings and use the thermal model to get an approximate reading of the windings

Trajectory Optimization on Hardware:

- Maxon EC-60 Brushless DC Motor (with temperature sensor)
- Proprietary Custom Motor Driver Board
- 1-DOF motor test stand and 1-DOF constrained hopper
- Link attached to motor designed to imitate load outside of range of nominal torque of motor specifications

Results

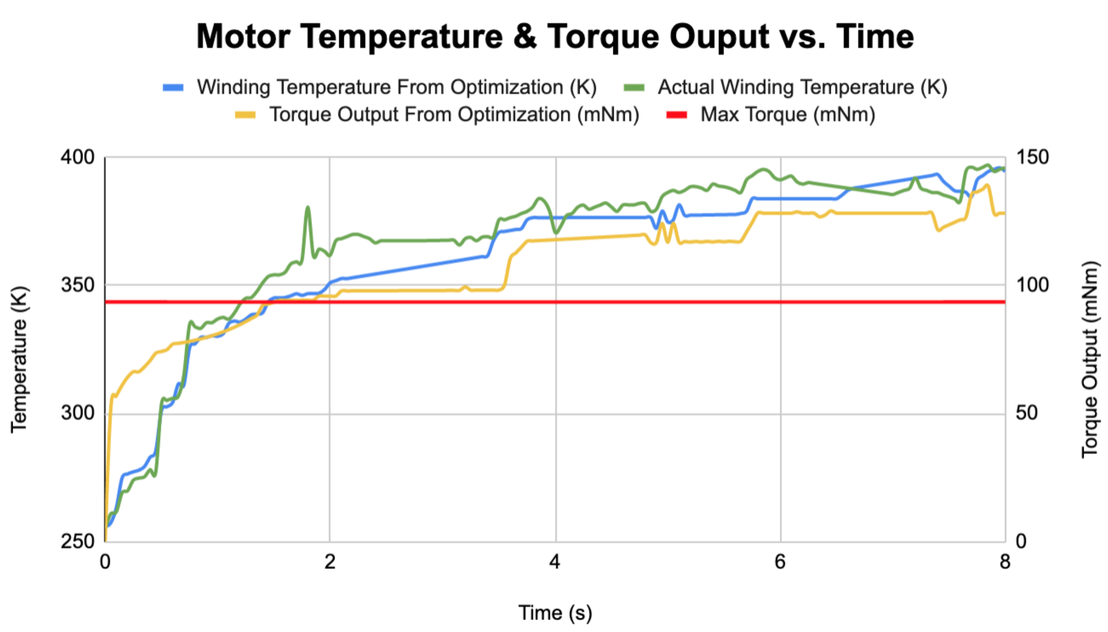


Figure: The result of the optimization framework on the single-DOF testbed which allowed the robot to pick increase the load almost 2 times it's nominally rated torque (Red Line, shown above). The blue and green graphs show the tracking performance of the temperatures from the optimization and the the actual hardware.

Future Work

- Hardware test of gait optimization to account for joints in a reduced operational state (i.e. motors which may no longer be working)
- Test validity across multiple motor manufacturers

References

[1] F. Grimminger et al., "An open torque-controlled modular robot architecture for legged locomotion research," *arXiv:1910.00093*, 2019.

[2] M. Posa, "Optimization for Control and Planning of Multi-contact Dynamic Motion," 2017.

[3] J. Urata et al., "Thermal control of electrical motors for high-power humanoid robots," *ICRA*, 2008.

Contact

{paarth, havoutis}@robots.ox.ac.uk

ludovic.righetti@nyu.edu