Electric motor and transmission sizing and optimization for dynamic robots, exoskeletons, and prosthetics.

Jason Cortell[1]

[1]Cornell University

[1]jbc2@cornell.edu

Summary

We present a set of calculations and heuristics such that, given the design goals of a legged machine (robot, exoskeleton, prosthetic device, etc.), a designer can make reasonable comparisons of the motor and transmission technologies available; and, having selected the basic technologies and products, further optimize parameters like motor size and gear reduction ratio.

These calculations and heuristics take into account requirements for peak joint torque and speed, sustained joint torque, maximum self-excited and external (negative-work) acceleration, cost of transport (COT), robot mass, and cost; the results include initial sizing of motors and transmission elements, targets for leg and "reflected" inertias, and stiffness of series-elastic elements.

Introduction

Where hydraulic actuators were once the only option for highly dynamic legged machines, the steady improvement of power-to-weight ratios in brushless electric motors, electronic controls, and batteries have made these solutions viable as well. This is not apparent in most robot bipeds so far, but the ones from Jonathan Hurst's lab [1] do well, and the Cheetah quadraped from Sangbae Kim's group [2] is an impressive demonstration of what is possible.

Further, the use of electromechanical actuators rather than hydraulic ones permits much better energy efficiency and lower cost, particularly at the human scale and below.

Performance metrics

Every legged machine will have some basic mechanical limits on its speed, strength, agility, and robustness. (These are not independent measures – speed is important for basic locomotion, for example, but also to moving limbs quickly to achieve more robust balance and agility.)

These are subject to the limits of the actuators, as follows:

Maximum speed of a motor is set, roughly, by the point at which the motor back EMF (voltage) equals the battery voltage: $V_{bat} = V_{BEMF} = K_v \omega$, where K_v is voltage constant and ω is speed. But, increasing the battery voltage or decreasing K_v for a given motor and controller design increases electrical losses, and there are mechanical limits and losses with high speed too.

Peak motor torque is limited by magnetic saturation of the laminations in the stator, demagnetization of permanent magnets in the rotor, or mechanical strength of the motor or transmission (assuming the battery and electronic controls can supply enough current.)

Peak joint acceleration is closely related to peak joint torque. When the motor is acting to accelerate the limb, via the transmission, acceleration is equal to the peak joint torque minus various drag torques, divided by the total limb inertia, including any "reflected inertia" from the motor rotor and transmission. We also look at an actuator's capability to "get out of the way" of an externally-applied impact torque.

High sustained or RMS joint torque is directly related to heat dissipation. More torque from an electric motor means more current in the windings and more heat to get rid of. This is highly dependent on the thermal design of the actuator, but we show the relative effectiveness of several cooling methods for an example motor. (Not discussed are the variety of clutches, springs, and variable-ratio transmissions that could reduce the motor load for a given joint torque.)

Energy efficiency and minimum COT are achieved by designing for minimal torque-related losses (approximately proportional to torque in the transmission, and to torque-squared in the motor) and speed-related losses (approximately due to some combination of constant plus viscous friction) for the expected primary gait of the machine.

References

[1] Ramezani, Alireza, et al. "Performance analysis and feedback control of ATRIAS, a three-dimensional bipedal robot." Journal of Dynamic Systems, Measurement, and Control 136.2 (2014): 021012.

doi: 10.1115/1.4025693

http://dynamicsystems.asmedigitalcollection.asme.org/article.aspx?articleid=1760199

[2] S. Seok et al., "Design Principles for Energy-Efficient Legged Locomotion and Implementation on the MIT Cheetah Robot," in IEEE/ASME Transactions on Mechatronics, vol. 20, no. 3, pp. 1117-1129, June 2015.

doi: 10.1109/TMECH.2014.2339013

http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6880316&isnumber=7109981