Actuator design for a high-performance legged biped robot

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1 Introduction

Humanoid robots in popular culture feature superhuman strength, speed, and agility, but the real-world versions still fall short of their human models. One well-known robot beginning to close that gap, however, is Boston Dynamics's ATLAS [1]. Good sensors and controls no doubt help, but arguably the largest factor in its performance is the sheer power of its hydraulic actuators. The high leg speeds and forces available permit fast and robust responses to external disturbances, such as those arising from a floor strewn with broken chunks of concrete [2]. However, ATLAS achieves this performance only via the infusion of large amounts of energy in the form of high-pressure hydraulic fluid, orders of magnitude more energy than would be needed by a human performing the same task. Besides being wasteful, this has the effect of tethering ATLAS to its energy source and putting severe limits on its useful range. Inefficiency is fundamental to conventional hydraulic actuators and controls, since their pumps must output full pressure and flow even if only a little is required by a robot. Efforts to address this problem with multiple system pressures, variable-displacement pumps, pressure accumulators, etc., result in rapid increases in system cost, weight, and complexity. Achieving acceptable efficiency in a human-scale robot, therefore, will require a different approach to actuators. Research at many institutions is under way to develop robot "muscles," actuators based on fibers and structures that contract when activated. However, we are not aware of any of these that have yet achieved useful levels of speed, force, and efficiency in a lightweight package. Therefore, we have focused our efforts on electromechanical actuators, which rival hydraulics in their power-to-weight ratios. In addition, digital switching controls for electrical power circuits allow these actuators to be quite efficient across their full range of output levels, and the hardware to do this is becoming steadily smaller, lighter, and less expensive. As we develop these electric actuators for our open-source bipedal robot platform, we aim to achieve as much as possible of the raw power and responsiveness of ATLAS's hydraulics, while maintaining high efficiency across a wide range of power levels.

2 Joint speed and torque requirements

Our proposed biped robot has a maximum design mass of 30 kg, with 0.8 m leg length and approximately 0.4 m thigh and shank lengths. We examine the joint load requirements, and thus the actuator requirements, for several cases:

1) Walking at normal speed
2) Running slowly (jogging)
3) Brief high-power maneuvers (a quick leg motion for balance, or a few stair steps; time scale on the order of a second or less)
4) Longer high-power maneuvers (one or more full flights of stairs, or a sprint; time scale on the order of ten seconds to one minute)

Lacking so far a fully-specified robot, joint power loads were estimated from published human subject data (e.g., [3]), scaled for robot body weight and expected mass distribution. To minimize the robot's energy consumption, we want to optimize power use during the most prevalent gait, which for this robot (and most humans) is walking. If this were the only demand placed on the actuators, we would tend to size them such that the joint loads involved in walking utilized a large fraction of the maximum power available from the motors. We could then use lightweight, low-power motors and controllers, and maintain high efficiency. But we also need the robot to be able to balance robustly, which requires fast, high-speed leg positioning (e.g., see the video of Boston Dynamics's BigDog slipping but not falling on ice). It would also be nice to have a robot that could run and climb stairs. Note, though, that these activities are infrequent, so even if their efficiency is relatively poor the effect on the total energy use is minimal.

3 Torque- vs. speed-related motor losses

Inefficiencies in electric motors can be grouped into two general categories: losses related to the speed of the motor, and losses related to creation of torque in the motor. Speed-related losses are often called iron losses, because they are dominated by hysteresis and eddy current losses in the iron core of the motor. Hysteresis in the magnetic domains in the core appears as a constant friction torque, while the eddy current torque is proportional to speed. The torque-related or copper losses are due to resistance heating of the windings, and are proportional to the square of the output torque. In general, for a given motor design, a smaller motor will have lower iron losses at a given speed (less iron to create drag), and a larger motor will have lower copper losses for a given torque. One interesting approach to motor sizing for a robot is to choose a small motor sized for walking, and then to overload it heavily during more strenuous activities. This might result in huge copper losses due to squaring the high winding current, but for brief periods the effect on overall efficiency is minimal. The thermal mass of the motor windings is high enough that it might not burn up for several seconds, and if it is cooled well enough the power level may be sustainable for longer activities [4]. This is particularly true for permanent magnet brushless motors, in which the stator coils are stationary and in contact with the case, well-positioned for heat sinks or water cooling jackets. (For brushed motors the magnets are on the outside and the windings are in the rotor, leaving few options for cooling.)

4 Motors

Our actuator design process began with Maxon motors, particularly their 4-pole brushless models. These have excellent heat transfer properties, allowing heat to be conducted quickly away from the windings and out of the motor. We later moved to motors designed to power large model airplanes. These had somewhat reduced heat transfer, but much better power-to-weight ratios (e.g., over 3 kW/kg continuous power) and improved efficiency. Another interesting advantage is that they are routinely custom-wound, allowing fine-tuning of both the torque constant (torque per amp) and the motor length, among other options.

5 Gear ratios

Although some researchers are pursuing designs in which the motor directly drives a leg joint, we found the best performance and lowest weight with relatively small motors and high gear ratios. Motor/gear combinations were evaluated for speed and torque losses in ankle, knee, and hip joint application during walking and slow running, as estimated from human torque and speed data. This allowed calculation of estimated overall energy efficiency for each combination during these activities. Taken alone, this process would have led to high gear ratios and peak motor speeds, and also to excessive levels of “reflected inertia” through the gearbox. The apparent moment of inertia of the motor, as measured at the output of the gearbox, is equal to the actual motor inertia multiplied by the square of the gear ratio. Put differently, the kinetic energy of the motor rotor increases as the square of the rotor speed, and it takes time to get it moving fast. As a result, the gear ratios were adjusted lower, giving improved response time and lower iron losses, but higher copper losses than would have been desirable otherwise. The motor size and weight was also somewhat increased, to create added torque.

6 Actuator bandwidth

Torque, speed, efficiency, and light weight are all critical features of a robot actuator, but so is something we could loosely call bandwidth. One bandwidth requirement relates to the time it takes to reposition the leg for balance after a sudden disturbance or trip. Interestingly, even for high transmission gear ratios, the motor inertia is still a small fraction of the leg inertia. Thus, the bandwidth will mostly be related to maximum torque at the joint, maximum joint speed, and leg moment of inertia. A second bandwidth requirement, of sorts, is in response to external impacts. If the leg swings into an external fixed object, like a wall, the foot stops immediately. This forces the gearbox and motor, with all of its kinetic energy, to stop immediately also, and very likely the gearbox will break as a result. Since impacts are essential to walking and running, one of the costs of using a gearbox is designing mechanisms to permit collisions safely.

7 Series springs and clutches

A stiff spring or other compliant element in series with the actuator can be thought of as a low-pass filter on the external collision, taking up a certain amount of the initial sudden change in velocity and allowing time for the motor and controls to respond appropriately. However, it also slows down the overall actuator response time, so the spring must be selected carefully [5]. A second helpful mechanism for managing collisions and falls is an overload clutch between the transmission and the joint, allowing slippage if torque values reach a level likely to damage the transmission. With angle sensors on both side of the clutch, this slippage can be detected and compensated for, allowing the robot to continue on its way.

8 Conclusion

Although still short of the capabilities of biological actuators (muscles), modern high-power magnets and motor control electronics, when combined with careful transmission design, create actuators capable of powering robots, prostheses, and exoskeletons in a wide variety of new autonomous applications.

References

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