Efficient and agile open-source bipedal robot

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1 Introduction

With our new robot, an open-source biped locomotion platform, we aim to approach human-level performance in all categories: endurance, agility, speed, and robust balance. This new robot is intended to traverse normal human built environments safely and reliably – sidewalks, floors, and eventually stairs – with minimal power use. With an energy cost of transport (COT) approximately that of a human, it should be able to walk over two hours on the charge in a 2 kg battery.

2 Target specifications

Leg length	0.8 m
Height, including torso and head	1.5 m
Hip and legs mass	20 kg
Total allowable mass	30 kg
Battery mass	2 kg
Battery capacity	230 W-hr
Cost of transport (COT), overall, walking	0.25
Joint torque (knee, thigh), continuous	75 Nm
Joint torque (knee, thigh), peak	200 Nm
Joint speed, maximum	15 rad/sec
Joint power, maximum	3 kW
Walking speed	1.5 m/s
Jogging speed	3 m/s

3 Design overview

Joint geometry. The planned robot has up to 12 degrees of joint freedom in the legs and hip. These include two in the ankle – powered ankle dorsiflexion/plantar flexion, passive inversion/eversion; one at the knee; and up to three at the hip. The hip is designed with three distinct joints forming a kinematic chain. At the top is the leg rotation joint, which initially will be locked (it may be fully implemented later if needed). Next down is leg adduction/abduction, and at the bottom is the leg swing joint, with an actuator physically located in the upper thigh.

Actuator design. A mobile robot needs actuators that are light, powerful, compact, robust, and efficient, and it would also be good if they were relatively quiet, for indoor use, and not too expensive. Traditional hydraulic systems achieve the first four of these goals rather well, but do poorly on efficiency, noise, and cost. Boston Dynamics appears to be pushing hydraulic design to reduce noise and improve efficiency, as demonstrated in their recent electrically powered/hydraulically-actuated robot dog, Spot [1]. In our design we push the limits of permanent magnet brushless motors and mechanical transmissions, matching each to the requirements of its joint. The motors and gear reduction were designed to meet five requirements:

1) Efficient generation of the torque and velocity profiles characteristic of human walking. Actuators were evaluated for cost of transport by simulating their use in a human walking gait [2].
2) Motor inertia and gear ratio low enough (i.e., low enough “reflected inertia”) to allow the robot to respond effectively to sudden external disturbances (e.g., stubs foot on rock). With the selected actuators the foot can be decelerated from the 3 m/s top speed of the robot to zero in about 10 ms, or a distance of about 3 cm. Shock loads in excess of that are to be absorbed by overload clutches near the joints.
3) Continuous leg torque sufficient for climbing stairs, squatting, etc. In a small motor, this generates a lot of heat. To enable this capability, the leg swing and knee motors will be fitted with water cooling jackets.
4) Robust and stable walking, we believe, requires fast foot placement for balance. The foot and lower leg are designed for minimal mass, and thus minimal leg inertia. This, combined with the high peak power of the actuators, should allow the foot to be repositioned 0.5 radians in any direction in less than 0.2 seconds.
5) Also required – foot placement accuracy. Our transmissions, using planetary gears and chain drives, can lead to backlash/play and foot placement error. We aim to keep foot position backlash below 2 cm.

Control electronics. Drawing upon our experience with the Ranger robot [3], we will use up to 20 low-level sensing and motor control microcontrollers communicating on a high-speed CAN bus network. These can operate at up to 300 MHz, allowing many control and sensing tasks to be moved down to the joint level if desired. They communicate with one or more top-level “main brains,” which will initially be the open-source BeagleBone Black, a TI ARM A8 processor running at 1 GHz.

The custom motor controllers are similar to those from

Ranger, but upgraded to three-phase brushless output and higher power. These can also be water cooled as needed.

For sensing, every joint will be fitted with a Hall-effect absolute angle sensor, as will the motors. In addition, every joint sensor board will also have three-axis rate gyros and accelerometers (since they cost so little! And could be quite useful.). An additional high-accuracy inertial measurement unit is planned for the torso, if needed. The feet are designed with ten resistive contact force sensors each, distributed across their bottoms. The motor controllers will provide motor current sensing and joint torque estimates.

References

[1] Boston Dynamics, https://www.youtube.com/watch?v=M8YjvHYbZ9w 2015

[2] D. Winter, "Biomechanics and Motor Control of Human Movement, Fourth Edition," John Wiley & Sons, Inc., 2009.

[3] P. Bhounsule, et. al., "Low-bandwidth reflex-based control for lower power walking: 65 km on a single battery charge," The International Journal of Robotics Research, 2014.