Design Principles for a Family of Direct-Drive Legged Robots

Gavin Kenneally[1], Avik De,[2] and D. E. Koditschek[2]

I. Introduction

A. Direct-drive robots

Direct-drive actuators (no gearbox) are desirable for robotics applications due to their lack of backlash, low friction, and high mechanical stiffness [1]. These actuators also facilitate the implementation of control strategies such as torque control [1], [2], impedance control [3], and virtual spring-damper systems [4] by removing the complicated dynamics associated with the gearbox.

Since gear ratios in robots are typically 20:1 to 300:1 [5]–[8], by removing the gearbox, mass specific torque (not power) becomes the first limiting resource in electromagnetically actuated robots [1], [2]. Adopting the perspective of locomotion as self-manipulation [9], the force/torque resource becomes even more scarce as the machine's payload must now include the mass of the robot itself. The design problems associated with actuator selection, configuration, recruitment, and leg kinematics must therefore address a central theme of mitigating the mass specific torque/force problem.

B. Contributions

This paper outlines the design of a family of direct-drive legged robots at the 2 - 5kg scale, whose dynamic performance (according to various measures detailed below) is comparable to or in some cases better than more established geared machines. These robots: Delta Hopper (a monoped with three active DOF/leg), Penn Jerboa (a tailed biped with one active DOF/leg) [10] and Minitaur (a quadruped with two active DOF/leg) share common electromechanical infrastructure and design strategies instantiated through very different morphologies. Notwithstanding their starkly different mechanics, these machines' common power train architecture affords the benefit of allowing (but of course in no way requiring) a compositional style of control promoting significant modularity, re-use and code sharing. Namely, we have found it straightforward and empirically effective to achieve a variety of interesting behaviors in each of them by recourse to the composition of simple, decoupled, low-dimensional controllers [11] that take particular advantage of the "transparency" direct-drive design confers [12] by relying heavily on proprioceptive touchdown detection. Apart from some very specialized machines [13], and those using direct-drive linear actuators [14], to the authors' best knowledge this family of machines represents the first examples of direct-drive legged robots using conventional rotary electromechanical actuators.

This work was supported by US Army Research Laboratory under Cooperative Agreement Number W911NF-10-2-0016 and National Science and Engineering Research Council of Canada 352093.

[1]Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, Philadelphia, PA, USA gake@seas.upenn.edu

[2]Department of Electrical and Systems Engineering, University of Pennsylvania, Philadelphia, PA, USA {avik,kod}@seas.upenn.edu

II. Motivation

A. Direct-drive for legged locomotion

In addition to the advantages of direct-drive in the context of manipulation, the collisions inherent to legged locomotion [15] also present opportunities for improvements in:

1) Mechanical robustness as there are no gears to protect from impulses.
2) Dynamic isolation of the body since it is only directly coupled to the legs through the motor's air gap and inertially coupled throught the motor's bearing (unless the leg Jacobian is singular).
3) Greatly improved actuator transparency [12] yielding good proprioceptive sensing.
4) High actuation bandwidth enabling arbitrary (up to force and sensing limits) virtual compliance.

In addition to the design challenges detailed below, the disadvantage of direct-drive machines is predominantly energetic efficiency as the operating point of the actuators must be brought closer to stall, resulting in increased Joule heating and decreased output power [16].

III. Design

A. Actuator selection

Since specific force is the first limiting resource, motors will be selected according to their thermal specific torque:

$$K_{ts} := \frac{K_t}{m}\sqrt{\frac{1}{R_{th}R}} \qquad (1)$$

expressed in $\frac{Nm}{kg^{\circ}C}$. K_t is the motor's torque constant ($\frac{Nm}{A}$), m the motor's mass (kg), R_{th} its thermal resistance ($\frac{^{\circ}C}{W}$), and R its electrical resistance. This measure includes a motor's desirable ability to produce torque at stall in addition to the inescapable production and dissipation of waste thermal energy caused by Joule heating. Thermal specific torque is similar to the dimensionless motor constant K_m ($\frac{Nm}{\sqrt{W}}$) [1] but takes mass and thermal dissipation into account. Generally, outrunners (rotor on the outside) will be preferrable to inrunners (rotor on the inside), and this measure is tied favorably to a motor's radius to depth ratio [1] as well as a large gap radius [2]. The measure is fundamentally winding invariant [17], but in practice other details of the motor's construction (especially relating to the stator core and volume of copper) are critical.

A plot of thermal specific torque against gap radius for a variety of motors representative of contemporary legged robot applications (and annotated by citation of a representative application) is given in Fig. 1. While motors within a series have a somewhat linear trend [2], two outliers are also shown: T-Motor U8 (used in this family of machines) and the custom motors made for the MIT Cheetah [18]. These demonstrate that the design of direct-drive machines must employ a degree of "inverse" motor sizing, where the dimensions of the machine are dictated by the size of a COTS motor identified with very good thermal specific torque. Even the the MIT Cheetah's excellent custom motors would not be suitable for direct-drive operation in a machine of that size (discussed further in Section IV) as their K_{ts} is almost double that of the U8s, whereas the Cheetah's mass is 6-15x larger than the robots in this family.

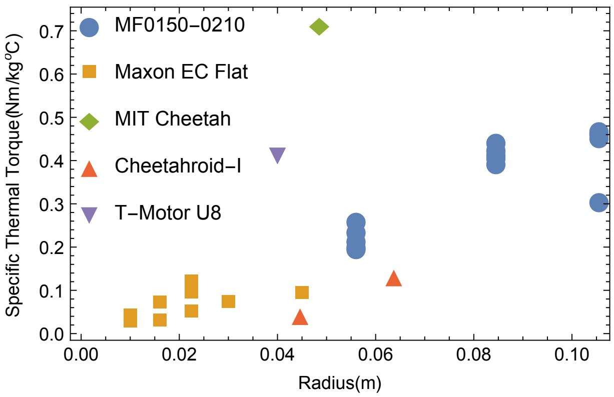

Fig. 1: Thermal specific torque vs gap radius for a representative sample of actuators used in contemporary legged robots: ATRIAS [6] (MF0150010 [19]), XRL [5] (EC45-70W [16]), MIT Cheetah [18] (custom), Cheetahroid-I [14] (custom) and this family of machines (T-Motor U8 [20]). Since the Allied Motion Megaflux (MF) motors are sold frameless, their mass has been increased by a half to account for bearings and frame. The MIT Cheeah's motors were assumed to have the same $R_{th} = 1\frac{^\circ C}{W}$ as the COTS motors they replaced. The linear motors in the Cheetahroid-I are approximated as angular motors by assuming their stroke is half an equivalent circumference. No thermal information is provided for these motors, so the optimistic assumption that "peak" force could be sustained indefinitely at a $100^\circ C$ rise was made. The thermal characterization of the T-Motor U8s was done empirically using a FLIR e4.

B. Actuator combination

When actuators are joined in series, the velocity of the end effector is the sum of the velocities of the individual motors, whereas when actuators are combined in parallel, it is the torques of the the individual motors that are summed (scaled by the link lengths in both cases) [25]. Given that electromagnetic motors are better powered at higher frequencies, operation near stall (that dominates the application domain of low-geared actuation for legged locomotion) implies that the motors should be combined in parallel wherever possible. The legs of our direct-drive robot family vary from one to three active DOF, and all legs with multiple active DOF (Minitaur and Delta Hopper) have the motors combined in parallel. Furthermore, the actuators are all co-located at the hip to minimize leg inertia [18].

C. Mass budgeting for robot specific power and force

It has long been understood in the legged locomotion design literature that as large as possible a fraction of the robot's mass budget should be reserved for actuation [26]. This strategy has been taken to an extreme as the robots in this family all have approximately 40% of total mass taken up by the actuators, compared to 24% for the modestly geared MIT Cheetah and approximately 10-15% for more conventional machines (detailed in Table. I).

D. Leg workspace and infinitesimal kinematics

In the case of Minitaur and Delta Hopper, by allowing the "knee" joints to operate above the "hip" joints, the workspace is doubled and the infinitesimal kinematics are made more favorable, resulting in 2.1x increase in energetic output in a single stride from a fixed power source and a 5x decrease in collision losses at touchdown compared to a more conventional design, as described in [17].

E. "Framing" costs

While increasing the number of active DOF/leg can improve control affordance, combining actuators incurs inescapable costs associated with replacing a single larger actuator by multiple smaller ones. When considering how a motor's output torque scales as the characteristic length is modified, the designer must decide how to scale the motors: isometrically, or by assuming a constant cross section and varying the gap radius[1]. For a constant actuator mass budget, as the number of actuators, n, increases and the actuators scale isometrically, the specific torque scales as $\propto n^0$ if the motors are added in parallel and $\propto n^{-1}$ if they are in series. If the actuators are instead scaled by gap radius, the specific force goes $\propto n^{-1}$ in parallel and $\propto n^{-2}$ in series[2]. This scaling argument represents the minimal characteristic rate of lost specific force production incurred by adding motors whereas, in practice, the additional motors accrue additional cost arising from the further increment of mass (and complexity) needed to frame and attach them.

IV. Performance Measures

Table I provides physical properties and performance measures for this family of direct-drive robots as well as examples of geared machines over a wide range of mass (1-60 kg).

A. Steady velocity (v_{ss})

Wherever possible, the maximum experimentally observed steady forward running speed of the robots of interest will be provided in m/s.

B. Vertical Specific Agility (α_v)

Specific agility as defined in [27] represents the "mass-normalized change in extrinsic body energy [during stance]". Motivated by tasks such as ledge ascent, this measure will be restricted in this context to jumps that have a significant vertical component, and rotational and horizontal translational components of the energy will be assumed negligible:

$$\alpha_v = h_{max} g \tag{2}$$

[1] The scaling choice depends on both the design objective and availability of COTS (or feasibility of making custom) actuators. A very small radius motor could not be constructed with the same gap cross sectional area as a much larger motor, and a very large radius motor with the same cross section might not be stiff enough for practical use (in each case it is at least feasible that an isometric motor could be bought/made.)

[2] Assuming constant density, the mass budget yields a volume budget, and so the volume of each actuator,v, will be the total volume budget divided by n, so $n \propto v^{-1}$. Scaling isometrically, mass $\propto l^3$ and torque $\propto l^3$ (as both the gap area and radius contribute to torque production), yielding specific torque $\propto n^0$ in parallel. In series, the torque at the end effector is the minimum of the torques in the chain (assuming constant link lengths), so at best $\propto n^{-1}$. If scaling is done according to gap radius, torque $\propto l^3$ but mass $\propto l^2$ resulting in specific force in parallel $\propto n^{-1}$ and similarly in series $\propto n^{-2}$

Robot	Legs	Active DOF	Mass (kg)	Motor Mass %	Gear Ratio	v_{ss} (m/s)	α_v (m/s)^2	a_{mcv} (g)
Minitaur	4	8	5	40	N/A	1.45	4.70	0.69
Delta Hopper	1	3	2.0	38	N/A	N/A	3.44	0.59
Jerboa	2	4	2.5	40	N/A	1.52	1.37	0.39
MIT Cheetah	4	12	33	24	5.8	6	4.48	1.33 (-0.60 w/o gearing)
XRL	6	6	8	11	23	1.54	4.17	1.14 (-0.91 w/o gearing)
ATRIAS	2	6	60	11	50	2.53	N/A	2.03 (-0.94 w/o gearing)
StarlETH	4	12	23	16	100	0.7	0.98	0.37 (-0.99 w/o gearing)
Cheetah Cub	4	8	1	16	300	1.42	N/A	19.38 (-0.93 w/o gearing)

TABLE I: Physical properties and performance measures of the machines of interest. For the MIT Cheetah, motor mass fraction was computed based on the custom high power actuators only, as the motor mass of the Dynamixels is negligible in comparison. The largest jump height was from steeplechase trials [21] which is certainly very conservative. The XRL v_{ss} is actually XRHex data [5]. ATRIAS v_{ss} from [22], and once again only the high power actuators are considered for the mass fraction. The StarlETH [23] jump height was taken from single leg data [24]. The Kondo KRS2350 servos in the Cheetah Cub [8] were assumed to have 1/3 motor mass, and "stall torque" was assumed to correspond to $100°C$ rise.

where h_{max} is the maximal experimentally observed vertical jump height of the machine, and g the gravitational constant.

C. Minimal continuous vertical acceleration (a_{mcv})

Since specific force is the first limiting resource, a measure is necessary to understand whether a given machine will even be able to support its own weight. The leg infinitesimal kinematics have significant influence, we consider the minimum continuous vertical force that can be exerted by the machine, and normalize by the gravitational force acting on its mass, then subtract one resulting an estimate of the minimal continuous vertical acceleration:

$$a_{mcv} := \frac{\min(EMA_v)\tau_c n_l}{mg} - 1 \tag{3}$$

where EMA_v is the leg's effective mechanical advantage in the vertical direction (using the approximate assumption that all legs have sufficient workspace for the links to be parallel), τ_c the thermally sustainable continuous torque (assumed to be a $100°C$ rise), and n_l the number of legs that can push vertically. This dimensionless number will indicate if the machine will be able to support its own weight at any point in the leg's workspace (≥ 0), and represents the instantaneous vertical acceleration of the body in units of gravitational constant. For comparisons with other machines, the measure is listed as designed and also if the machine's gearbox were removed.

V. Conclusion

In this paper, we seek to outline the insights that led to the construction of a novel family of direct-drive legged machines with custom drive electronics (based on [28], detailed in [10]) with similar performance to their more refined, geared, counterparts. The forward running speed, v_{ss} of these machines is comparable, and vertical jumping performance, α_v is better than other machines at a similar scale ($\leq 30kg$). Furthermore, as judged by a_{mcv}, not only are these machines novel in their use of rotary motors without a gearbox, but the other machines considered would have very limited performance if their gearboxes were removed. The emerging design insights represented by the present family of machines demonstrates progress in mitigating the typical power/proprioception tradeoff for electromagnetic machines, and future work will explore other tasks and behaviors that can take advantage of good transparency in a dynamic machine.

References

[1] H. Asada and K. Youcef-Toumi, *Direct-drive robots: theory and practice*. MIT press, 1987.

[2] S. Seok, A. Wang, D. Otten, and S. Kim, "Actuator design for high force proprioceptive control in fast legged locomotion," *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2012.

[3] N. Hogan, "Impedance control: An approach to manipulation," *American Control Conference, 1984*, no. March, 1984.

[4] M. H. Raibert and Others, *Legged robots that balance*. MIT press Cambridge, MA, 1986, vol. 3.

[5] K. Galloway, G. Haynes, and B. Ilhan, "X-RHex: A highly mobile hexapedal robot for sensorimotor tasks," 2010.

[6] J. Grimes and J. Hurst, "The design of atrias 1.0 a unique monopod, hopping robot," *International Conference on Climbing and Walking Robots*, 2012.

[7] M. Hutter, C. Remy, M. Hoepflinger, and R. Siegwart, "Efficient and Versatile LocomotionWith Highly Compliant Legs," vol. 18, no. 2, 2012.

[8] a. Sprowitz, a. Tuleu, M. Vespignani, M. Ajallooeian, E. Badri, and A. J. Ijspeert, "Towards dynamic trot gait locomotion: Design, control, and experiments with Cheetah-cub, a compliant quadruped robot," *The International Journal of Robotics Research*, vol. 32, 2013.

[9] A. M. Johnson and D. E. Koditschek, "Legged Self-Manipulation," *IEEE Access*, vol. 1, no. 33, 2013.

[10] A. De and D. E. Koditschek, "The penn jerboa: A platform for exploring parallel composition of templates," *arXiv preprint arXiv:1502.05347*, 2015.

[11] ——, "Parallel composition of templates for tail-energized planar hopping," *IEEE International Conference on Robotics and Automation*, 2015.

[12] D. Lawrence, "Stability and transparency in bilateral teleoperation," *Robotics and Automation, IEEE Transactions on*, vol. 9, no. 5, 1993.

[13] R. S. Wallace, "Miniature direct drive rotary actuators. ii. eye, finger and leg," *IEEE International Conference on Robotics and Automation*, 1994.

[14] B. Na, H. Choi, and K. Kong, "Design of a direct-driven linear actuator for a high-speed quadruped robot, cheetaroid-i," *Mechatronics, IEEE/ASME Transactions on*, vol. 20, no. 2, 2015.

[15] A. Chatterjee and A. Ruina, "A new algebraic rigid-body collision law based on impulse space considerations," 1998.

[16] M. Motors, "Maxon catalog, key information," 2014.

[17] G. Kenneally and D. E. Koditschek, "Leg Design for Energy Management in an Electromechanical Robot," *Submitted-IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2015.

[18] S. Seok, A. Wang, D. Otten, J. Lang, and S. Kim, "Design principles for highly efficient quadrupeds and implementation on the MIT Cheetah robot," *IEEE International Conference on Robotics and Automation*, 2013.

[19] Allied motion datasheet. [Online]. Available: http://www.alliedmotion.com/

[20] T-motor u8 datasheet. [Online]. Available: http://www.rctigermotor.com/

[21] Mit cheetah robot lands the running jump. [Online]. Available: http://newsoffice.mit.edu/2015/cheetah-robot-lands-running-jump-0529

[22] Atrias robot: 9.1 kph running speed (5.7 mph). [Online]. Available: https://www.youtube.com/watch?v=U4eBRPHYCdA

[23] M. Hutter, M. Gehring, M. Bloesch, A. H. Mark, C. D. Remy, R. Y. Siegwart, A. H. Mark, A. H. Mark, R. Y. Siegwart, and R. Y. Siegwart, *StarlETH: A compliant quadrupedal robot for fast, efficient, and versatile locomotion*. World Scientific, 2012.

[24] P. Fankhauser, M. Hutter, M. Bloesch, and R. Siegwart, "Reinforcement learning of robotic legged locomotion."

[25] A. L. Ruina and R. Pratap, *Introduction to statics and dynamics*. Preprint for Oxford University Press, 2008.

[26] H. Rad, P. Gregorio, and M. Buehler, "Design, modeling and control of a hopping robot," vol. 3, 1993.

[27] J. M. Duperret, G. D. Kenneally, J. L. Pusey, and D. E. Koditschek, "Towards a comparative measure of legged agility," June 2014.

[28] M. Piccoli and M. Yim, "Cogging torque ripple minimization via position based characterization," in *Proceedings of Robotics: Science and Systems*, 2014.