Dynamic Legged Locomotion for Palm-Size Robots

David Zarrouk[b], Duncan W. Haldane[a], and Ronald S. Fearing[c]

[a]Dept. of Mechanical Engineering, UC Berkeley, Berkeley, CA USA
[b]Dept. of Mechanical Engineering, Ben Gurion University, Israel
[c]Dept. of EECS, UC Berkeley, Berkeley, CA USA

ABSTRACT

Minimally-actuated palm-size robots are capable of running at speeds greater than 2 meters per second (20 body lengths per second), with leg stride rates of greater than 20 Hz. In this dynamic regime, passive stabilization is needed for roll-and-pitch instability. However, we have found that certain roll-oscillation modes can be used for continuous high speed turning. Other continuous turning modes have also been identified, such as modulating foot contact location through foot compliance, and controlling differential leg velocity. For the small minimally-actuated robots examined, the dynamically enhanced roll-steer mode showed the best turning rate, of over 8 degrees per step, but only appears at certain running frequencies. Interstride phase and velocity control appears promising as a mode for in-plane maneuverability for under-actuated robots.

Keywords: legged locomotion, robot steering, minimally actuated robots

1. INTRODUCTION

Maneuverability of small underactuated robots is an important problem and has received wide study. These include the 6 legged RHex robots,[1–4] and rapidly-prototyped palm-size robots.[5–12] To examine limits of maneuverability, a single actuator turning robot 1Star,[13–16] was studied. Even smaller robots at the several gram range such as miniRoACH,[17] and HAMR[18, 19] have been considered. For extra maneuverability, dynamic tails can be used to effect turns while running.[20–22] Fully articulated legged robots, with considerably more active degrees of freedom, such as Tsujita et al. 2005,[23] Scout,[24] Rise,[25] and StarlETH[26] have a wider range of turning strategies which are not considered here. The principles underlying legged maneuverability, particularly in the horizontal plane, have also been extensively studied, for example Aoi et al.[27] Blickan et al.,[28] and Burden et al.[29] Full et al.[30] Jindrich and Full[31] Revzen and Gluckenheimer,[32] and Spagna et al.[33]

A comprehensive overview of turning methods in legged robots, particularly applicable for minimally actuated robots, can be found in McClung.[34] In this paper, we look specifically at steering methods which have been applied to 1 or 2 actuator palm-size robots, specifically OctoRoACH, 1Star, and VelociRoACH. Although these robots have low complexity, they have achieved turn rates which are comparable to more complicated robots.

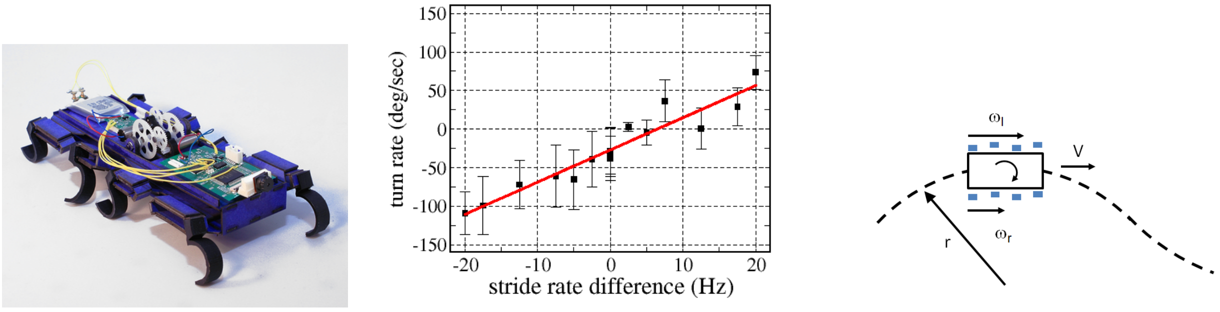
2. METHODS AND EXPERIMENTS

Turning strategies were examined in 3 robots: OctoRoACH, 1Star, and VelociRoACH. These robots are all minimally actuated with either 1 or 2 motors on each robot.

For OctoRoACH,[9] an 8 legged robot with one motor per side, leg velocity was controlled independently on each side, with the expectation that the faster side would be on the outside of a turn (Fig. 1). Somewhat consistent turning behavior is observed, and a gyro-based controller was used to control heading.

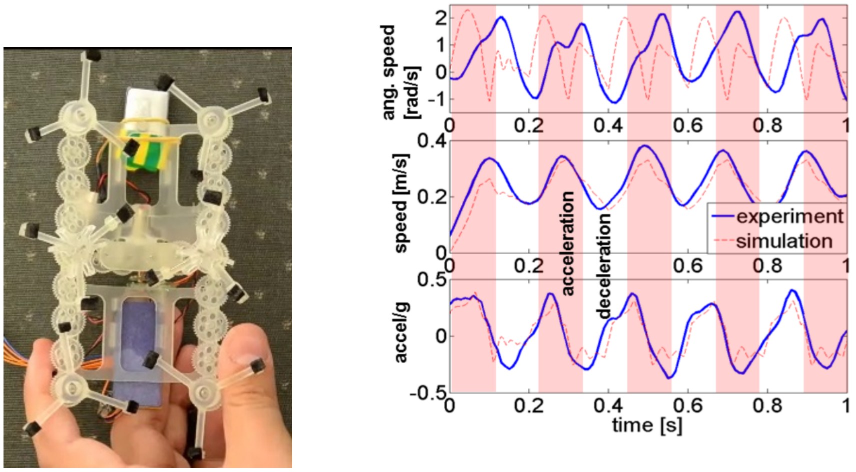
To examine minimally actuated steering, 1Star, a single actuator hexapedal "whegs-style" robot was constructed (Fig. 2a.) For 1Star,[13–16] we found a novel dynamic gait to control in-plane locomotion (forward, back, clockwise and counter clockwise rotations) of a compliant legged hexapedal robot using a single actuator. The gait exploits the compliance disparity between alternate stance tripods, to generate rotation by controlling the acceleration of the robot. The turning performance is shown in Fig. 2b.

Further author information: (Send correspondence to RSF)
RSF: E-mail: ronf@eecs.berkeley.edu, Telephone: 1 510 542-9193
DWH: E-mail: dhaldane@berkeley.edu
DZ: E-mail: zadavid@post.bgu.ac.il



a) b) c

Figure 1. a) OctoRoach 8 legged robot from Pullin et al. 2012.[9] b) Turning response with unsynchronized velocity control (from[9]). Differential (treaded vehicle) type steering, with higher leg speed on on outside radius. (From Pullin et al. 2012[9]).



a) b)

Figure 2. a) 1Star 1 actuator steerable robot[16] b) Turning response with leg acceleration and deceleration.[16]

The VelociRoACH[7] is a 10 cm long, 30 gram hexapedal millirobot capable of running at 2.7 m/s, making it one of the fastest legged robot built to date, relative to scale. For VelociRoACH, we explored a family of phase locked turning gaits where all legs of the robot move at the same speed[11] (Fig. 3). These gaits are highly periodic, allowing the vertical height and roll angle of the robot to be approximated by single harmonic sinusoidal functions. We demonstrated that oscillations in height and roll angle determine the robots turning behavior, and obtained a new high speed turning gait (forward velocity: 0.4 m/s, turn rate 200 degrees per second).[7]

The differential velocity approach to steering as shown for OctoRoach (Fig. 1), combines both phase and dynamic uncertainty, as legs are running at the 10 to 20 Hz rate. To reduce dynamic effects, a set of experiments was performed on VelociRoACH using 600 ms or 500 ms stride period on each side. In this way, the faster side starts a stride with a progressive 60° phase advance. As can be seen in Fig. 4, certain leg phase combinations give rise to net yaw rotation with a single stride. The third row in the plot shows the net rotation at the start of the next 600 ms leg period. (Most likely due to construction variations, right turns were less effective than left turns.)

It is worthwhile to compare the minimally actuated turning methods presented here with previous work. Two metrics are considered: first, a combined running and turning metric, and second, a quasi-static metric of turning per step. (Rapidly induced turns, such as from a dynamic tail, e.g. Kohut et al. 2012,[22] can give even

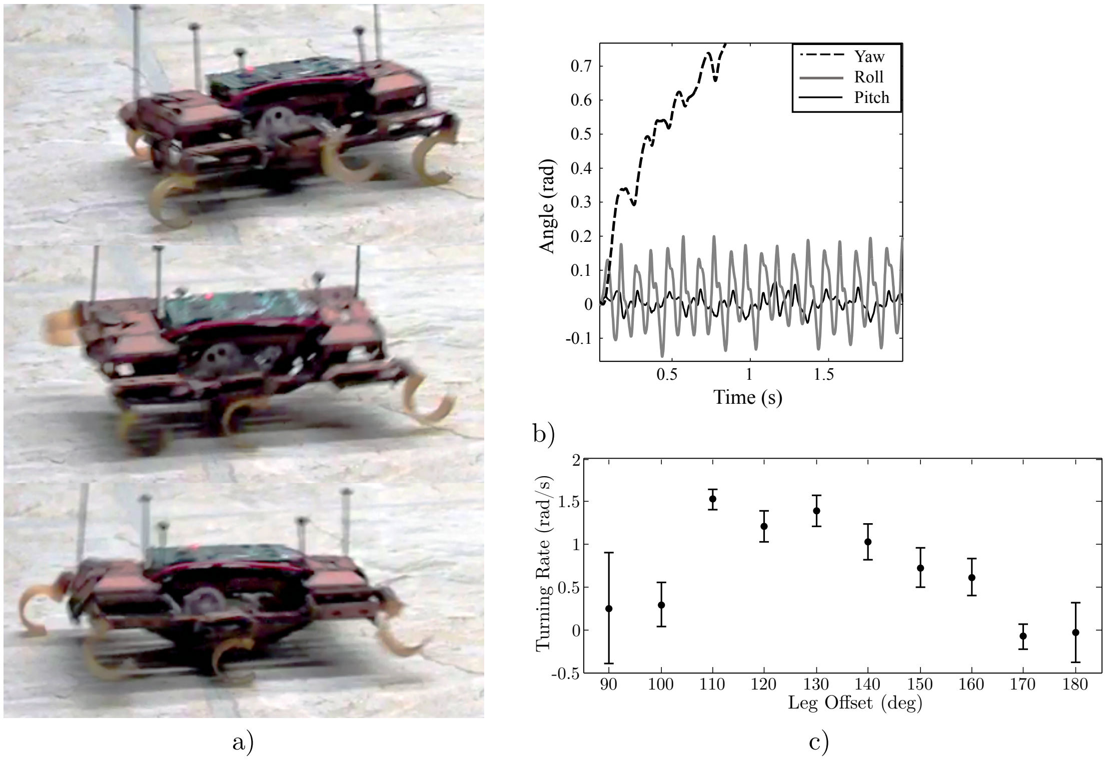


Figure 3. a) VelociRoACH in roll-oscillation turn, from Haldane et al.[11] b) Example turn at 5 Hz leg drive, and 110° phase offset between sides.[11] c) Turning response with phase difference between left and right sides.[11]

Table 1. Comparison of legged turning performance

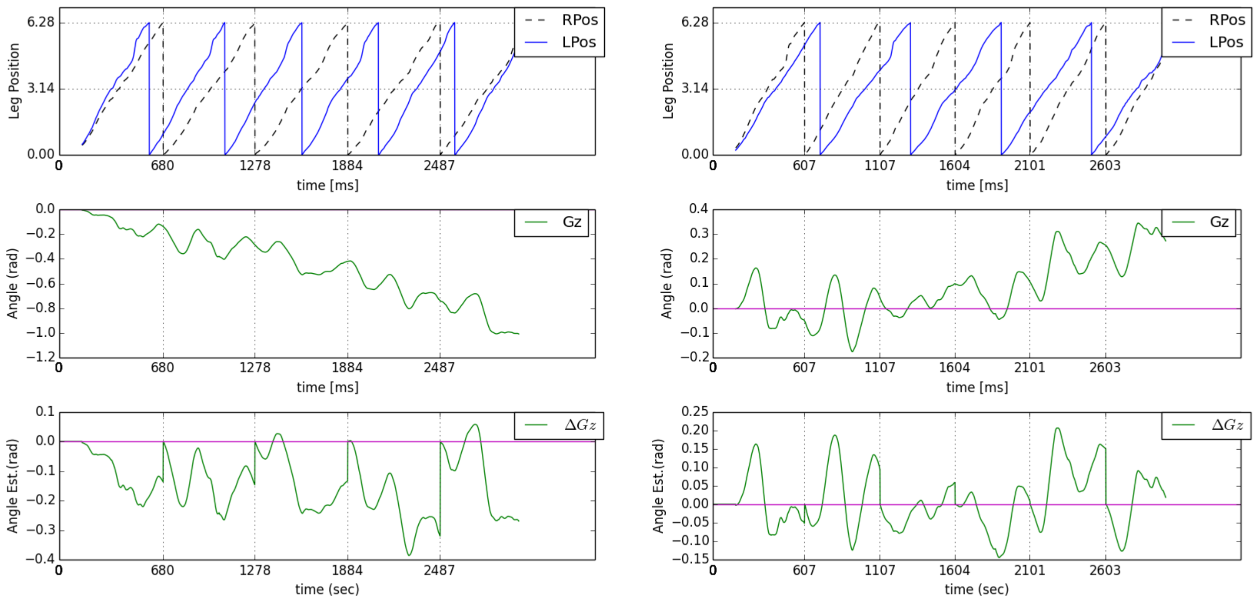
Robot	# Legs	# Actuators	$\dot{\psi}v(^\circ ms^{-2})$	steps/sec	°per step
RHex[1]	6	6	4.2	4	2.7
X-RHex[4]	6	6	1.44	2.2	3.6
iSprawl[34, 35]	6	3	50	28	1.8
Sprawlette[34]	6	12	18	16	2.2
OctoRoACH[9]	8	2	36.0	24	1.9
SailRoACH[21]	6	3	134	42	1.4
VelociRoACH 5Hz Turning[11]	6	2	29.1	10	8.6
VelociRoACH 8Hz Turning [11]	6	2	82.5	16	12.9
VelociRoACH 2Hz/1.66 Hz	6	2	4.4	4	5.7
1Star[16]	6	1	5.5	10	2.7
miniRoach[17]	6	2	.045	6	14.3
HAMR[19]	4	6	37.5	80	1.9

higher performance while running, but here the comparison is restricted to continuous turning locomotion.) A metric for turning performance, as noted by McClung,[34] combines forward speed v with angular turning rate $\dot{\psi}$:

$$K = \dot{\psi}v. \tag{1}$$

This metric is not scale-invariant, which gives a natural maneuverability advantage to high-speed running robots with high turning rates, such as iSprawl.

An alternative metric is to examine the heading change per step while running. For an alternating tripod gait at 2 Hz, there are 4 contact events per second, with one event for each tripod. This data is not reported



a) b)

Figure 4. a) VelociRoACH turning with 1.66 Hz on right side legs, and 2Hz on left side. b) VelociRoACH turning with 1.66 Hz on left side legs, and 2Hz on right side. Angle estimate is from integrated rate gyro data, and last row shows net change for each leg cycle.

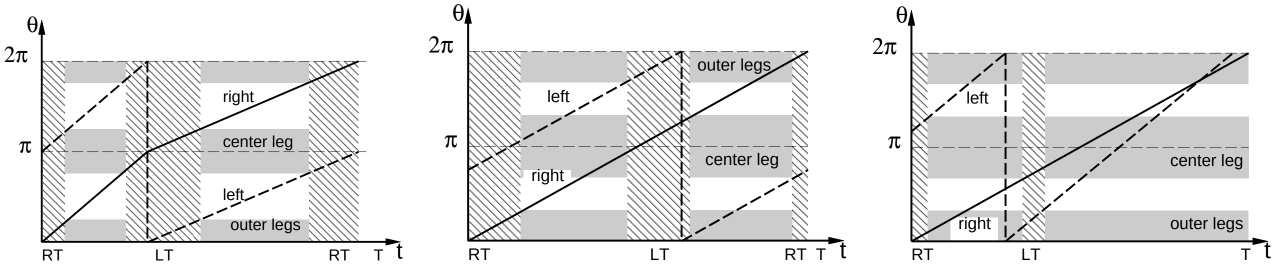
for most minimally actuated robots, but can be estimated from the average turning rate and the step rate. This data is summarized in Table 1, where the turning rate is estimated with robots running forward, i.e. not only turning in place. It is curious to note that turning rates are modest without much variation between robots which range from 30 gram range to multi-kg range.

3. MODELS FOR TURNING

Although a variety of turning modes have been considered in the previous section for several underactuated legged robots, it is striking that many robots have a similar limited turn-per-step as shown in Table 1. The table includes quasistatic and dynamic robots with several orders of magnitude mass difference. (MiniRoACH[17] has a high turn rate per step, but its gait can be characterized as a small jump-turn more than a steady step.) To look for similarities underlying the different gaits, the "Buehler clock" introduced in Saranli et al. 2001[1] maps out phase relationships in an alternating tripod gait.

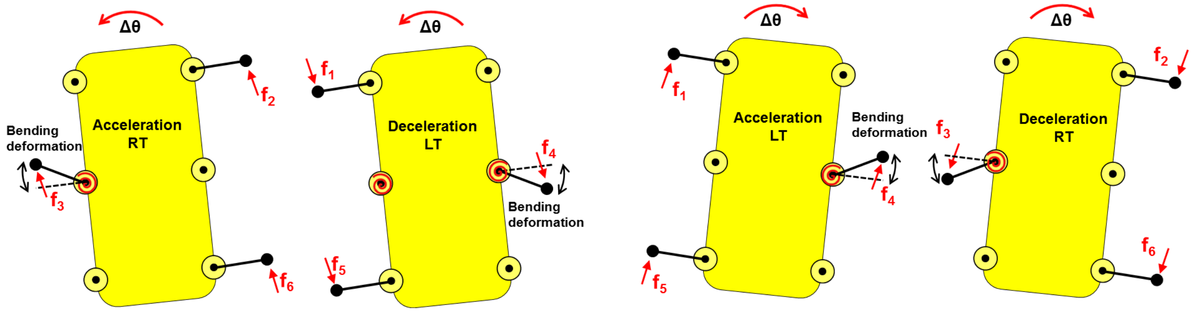
In a 6 legged robot such as RHex,[1] left and right tripods of legs can controlled relatively independently. For the minimal robots presented in the previous section, this is not the case. For VelociRoACH, one motor drives all three legs on each side, which are controlled by the leg drive linkage such that the center and front/back legs are 180° out of phase. Consider the right leg tripod (RT) composed of the right front and rear legs and the middle left leg. The left center leg velocity in contact can only be independent of the left tripod (LT) if the left front and rear legs are not in ground contact. For 1Star, since all legs are driven by the same motor, again the tripods RT and LT can only be independent in the case that a single tripod of legs is in contact ith the ground. The gear train enforces the 180° phase difference between left and right sides.

Given the constraints above, an equivalent "Buehler clock" is shown conceptually for 1Star, VelociRoACH with roll oscillation, and VelociRoACH with variable velocity in Fig. 5abc. In dynamic locomotion, with a 6 legged robot, there are $2^6 = 64$ possible combinations of leg contacts, and also body contacts with the ground. As a simplifying assumption, we neglect body contact, and highlight only the regions of leg angles which correspond to a tripod stance. (It might be argued that regions of operation with more than 3 legs in contact with the ground may not be well suited for turning.) For example, if the right side legs are at 0 or 2π (front and back



a) 1Star b) VelociRoACH roll c) VelociRoACH differential

Figure 5. Timing diagram for left and right side leg phase. For the right side, 0 and 2π rad correspond to front and back legs in center of contact. π corresponds to center leg in center of its contact. Horizontal bands show approximate extent of contact region. The Left Tripod LT corresponds to the 2 left outer legs in contact, and right center leg, and conversely for the Right Tripod RT. a) 1Star with one actuator driving left and right sides. b) VelociRoACH with phase offset, using roll mode to turn. c) VelociRoACH using faster outside legs to turn.



a) b)

Figure 6. Tripod model for turning, including center leg compliance and acceleration/deceleration from Zarrouk and Fearing (2015).[16] a) Left turn. b) Right turn.

in contact), and the left side legs are at π (only center leg in contact) this is considered a right tripod stance as noted by the RT label.

For the leg velocity profile for 1Star shown in Fig. 5a, the leg accelerates in the middle of RT (at t=0,T,...), and decelerates in the middle of LT. This acceleration/deceleration profile gives rise to a left step as explained in Fig. 6a. In this model, due to compliance, the left center leg (with twice the load of the outer legs), deforms, and travels a shorter distance than the right outer legs during RT. With displacement of the left side ΔX_l, and displacement of the right side ΔX_r, the net rotation per step is

$$\Delta\theta = \frac{\Delta X_r - \Delta X_l}{w + 2L_{leg}} \tag{2}$$

where w is the width of the robot body, and L_{leg} is leg length. (For details see Zarrouk and Fearing (2015).[16]) The amount of rotation per step is limited by friction at the center leg, and the dynamic simulation[16] predicts $\approx 5.6°$ per step, twice the experimental value of $\approx 2.7°$ per step noted in Table 1.

For the leg velocity profile for VelociRoACH in a roll induced turn, the nominal leg phasing is shown in Fig. 5b. In the experiment at 5 Hz in Haldane and Fearing (2014),[11] the left side leads the right side by a phase offset of 110°. Due to dynamic effects, a roll oscillation of ±6° is induced, which tends to increase foot normal loading during the contact (Fig. 7), and hence allow larger thrust forces (assuming thrust force limited by friction). This increased normal load is presumably responsible for the impressive 8.6° per step, higher than any of the other steady state turning rates in Table 1.

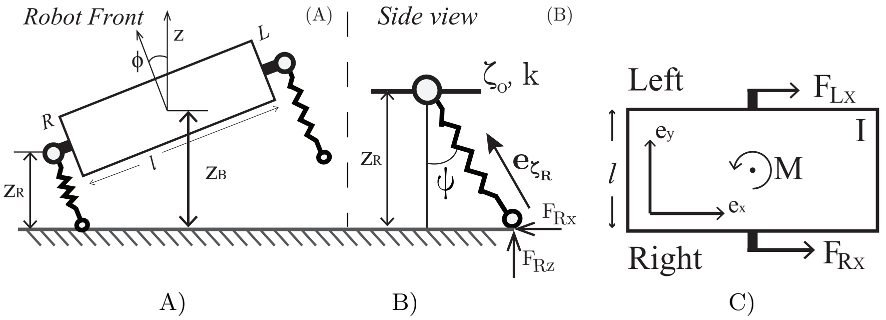


Figure 7. A) A leg-spring model for a running robot, showing the effect of z height and roll on foot loading). B) Leg forces are determined by approximating the leg as a spring and finding the net force given the kinematic variables. C) Top view of robot, showing turning moment generated by imbalance in leg forces. (From Haldane and Fearing 2014[11]).

The timing of the roll with respect to the foot contact phase determines whether the yaw moment is increased or diminished. If the leg spring decompresses after middle of stance, there is increased turning moment. It is worth noting that the phasing shown in Fig. 5b shows alternate tripods with equal velocity, not accounting for a turning moment. As reported in Haldane,[11] the phase of the roll moment with respect to the leg phase is critical for large turning (Fig. 3), and this roll-turn effect is only seen at a few running frequencies such as 5Hz and 8 Hz.

The differential velocity mode for tank-like steering (Fig. 1c) is attractive for its simplicity. However, with different velocities on left and right sides, phasing is in effect random, and OctoRoACH turning rates have high variance ((Fig. 1b), and the turn per step is only 1.9°. (VelociRoACH with 6 legs, also has difficulty with consistent turning with the differential velocity approach.) An example leg phase plot for 1.66 Hz (right side) and 2 Hz (left side) is shown in Fig. 5c. Due to leg phasing, a small fraction of leg contact time will be in left or right tripod configurations. Of particular note, is that at $\approx t = T/2$, both center legs are nominally in contact, and this bipedal configuration is not statically stable, and other legs will also be in contact. As shown in Fig. 4b, only one phase offset gives rise to a large net turn per step of 5.6°. Comparing the OctoRoACH and VelociRoACH at 2 Hz (Table 1) turns per step, it could be the case that many of the steps with random phase do little to contribute to net turning.

4. CONCLUSIONS

Three strategies for turning in underactuated legged robots were examined. The roll-turn strategy, which increases dynamic loading and hence foot thrust, is particularly effective from an angle per step perspective. The one actuator 1Star robot also dynamically loads one foot preferentially, giving rise to a net turning moment. Simple differential control of leg velocity seems to be less effective, as with feet slipping in a turn, the net thrust forces on each side may be fairly similar. In the quasi-static case, the turning observed with differential velocity probably relies more on stance variation, in particular, leaving regions of stable left or right tripods.

Dynamic continuous roll-enhanced turning is particularly effective, showing greater turn per step than any of the other published continuous leg-induced steering for minimally actuated robots. (Of course, robots with more articulated legs, e.g. StarlETH,[26] have the ability to generate quasi-static kinematic turns without these limits.) However, the VelociRoACH large steering response is limited to certain gait frequencies (e.g. 5Hz or 8z).

Control of steering in legged robots using differential velocity may be effective for turning, but only if the relative phase of the sides can be controlled for each stride. Resetting the leg phase for each stride could reset the turning step, or introduce extra steps with no net turning, reducing the effective turn per step. In addition, further work needs to be done to distinguish the effects of velocity from phase offsets. For VelociRoACH, a quasi-static target of a continuous 5° per step appears achievable, and would be significantly better than most other underactuated robots have so far obtained.

ACKNOWLEDGMENTS

This work was sponsored by the United States Army Research Laboratory under the Micro Autonomous Science and Technology Collaborative Technology Alliance. We thank the members of the Biomimetics Millisystems Labs for their assistance. Thanks to J. Goldberg for the iPython notebook for telemetry data.

REFERENCES

[1] Saranli, U., Buehler, M., and Koditschek, D. E., "RHex: A Simple and Highly Mobile Hexapod Robot," *The International Journal of Robotics Research* **20**, 616–631 (July 2001).

[2] Galloway, K. C., Clark, J. E., Yim, M., and Koditschek, D. E., "Experimental Investigations into the Role of Passive Variable Compliant Legs for Dynamic Robotic Locomotion," in [*IEEE Int. Conf. Robot. Autom.*], 1243–1249 (2011).

[3] Galloway, K. C., Johnson, A. M., Plotnick, B., Knopf, R., White, M., and Koditschek, D. E., "X-RHex : A Highly Mobile Hexapedal Robot for Sensorimotor Tasks," tech. rep., University of Pennsylvania (2010).

[4] Ordonez, C., Gupta, N., Collins, E. G., Clark, J. E., and Johnson, A. M., "Power modeling of the XRL hexapedal robot and its application to energy efficient motion planning," *CLAWAR* (118), 689–696 (2012).

[5] Birkmeyer, P. M., Peterson, K., and Fearing, R. S., "DASH : A dynamic 16g hexapedal robot," *IEEE Int. Conf. Intell. Robot. Syst.* , 2683–2689 (2009).

[6] Birkmeyer, P. M., Gillies, A. G., and Fearing, R. S., "CLASH: Climbing vertical loose cloth," *2011 IEEE/RSJ Int. Conf. Intell. Robot. Syst.* , 5087–5093 (Sept. 2011).

[7] Haldane, D. W., Peterson, K. C., Garcia Bermudez, F. L., and Fearing, R. S., "Animal-inspired Design and Aerodynamic Stabilization of a Hexapedal Millirobot," *IEEE/RSJ Int. Conf. Robot. Autom.* (2013).

[8] Hoover, A. M., Burden, S., Fu, X. Y., Sastry, S. S., and Fearing, R. S., "Bio-inspired design and dynamic maneuverability of a minimally actuated six-legged robot," *3rd IEEE EMBS Int. Conf. Biomed. Robot. Biomechatronics* (2010).

[9] Pullin, A., Kohut, N. J., Zarrouk, D., and Fearing, R. S., "Dynamic turning of 13 cm robot comparing tail and differential drive," *IEEE Int. Conf. Robot. Autom.* , 5086–5093 (2012).

[10] Hoover, A. M. and Fearing, R. S., "Fast scale prototyping for folded millirobots," *IEEE Int. Conf. Robot. Autom.* , 886–892 (2008).

[11] Haldane, D. W. and Fearing, R. S., "Roll oscillation modulated turning in dynamic millirobots," *IEEE Int. Conf. Robot. Autom.* (2014).

[12] Brown, C., Vogtmann, D., and Bergbreiter, S., "Efficiency and effectiveness analysis of a new direct drive miniature quadruped robot," in [*IEEE Int. Conf. on Robotics and Automation*], 5631–5637 (May 2013).

[13] Zarrouk, D. and Fearing, R. S., "1star, a one-actuator steerable robot," in [*Robotics and Automation (ICRA), 2014 IEEE International Conference on*], 2569–2569, IEEE (2014).

[14] Zarrouk, D., Pullin, A., Kohut, N., and Fearing, R. S., "Star, a sprawl tuned autonomous robot," in [*Robotics and Automation (ICRA), 2013 IEEE International Conference on*], 20–25, IEEE (2013).

[15] Zarrouk, D. and Fearing, R. S., "Compliance-based dynamic steering for hexapods," in [*Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on*], 3093–3098, IEEE (2012).

[16] Zarrouk, D. and Fearing, R., "Controlled in-plane locomotion of a hexapod using a single actuator," *Robotics, IEEE Transactions on* **31**, 157–167 (Feb 2015).

[17] Hoover, A., Steltz, E., and Fearing, R., "RoACH: An autonomous 2.4 g crawling hexapod robot," *IEEE Int. Conf. Intell. Robot. Syst.* (2008).

[18] Hoffman, K. L. and Wood, R. J., "Passive undulatory gaits enhance walking in a myriapod millirobot," *IEEE/RSJ Int. Conf. Intell. Robot. Syst.* **2**, 1479–1486 (2011).

[19] Baisch, A. T., Ozcan, O., Goldberg, B., Ithier, D., and Wood, R. J., "High speed locomotion for a quadrupedal microrobot," *Int. J. Rob. Res.* (May 2014).

[20] Chang-Siu, E., Libby, T., Tomizuka, M., and Full, R. J., "A lizard-inspired active tail enables rapid maneuvers and dynamic stabilization in a terrestrial robot," *IEEE/RSJ Int. Conf. Intell. Robot. Syst.* , 1887–1894 (Sept. 2011).

[21] Kohut, N. J., Peterson, K. C., Zarrouk, D., and Fearing, R. S., "Aerodynamic Steering of a 10 cm High-Speed Running Robot," *IEEE/RSJ Int. Conf. Intell. Robot. Syst.* (2013).

[22] Kohut, N. J., Pullin, A. O., Haldane, D. W., Zarrouk, D., and Fearing, R. S., "Precise Dynamic Turning of a 10 cm Legged Robot on a Low Friction Surface Using a Tail," *IEEE Int. Conf. Robot. Autom.* (2013).

[23] Tsujita, K., Toui, H., and Tsuchiya, K., "Dynamic turning control of a quadruped locomotion robot using oscillators," *Advanced Robotics* **19**(10), 1115–1133 (2005).

[24] Poulakakis, I., Smith, J. A., and Buehler, M., "Modeling and Experiments of Untethered Quadrupedal Running with a Bounding Gait: The Scout II Robot," *Int. J. Rob. Res.* (2005).

[25] Autumn, K., Buehler, M., Cutkosky, M. R., Fearing, R. S., Full, R. J., Goldman, D. I., Groff, R., Provancher, W., Rizzi, A. A., Saranli, U., Saunders, A., and Koditschek, D. E., "Robotics in scansorial environments," *Proc. SPIE* **5804**, 291–302 (2005).

[26] Hutter, M., Gehring, C., Bloesch, M., Hoepflin ger, M. A., Remy, C. D., and Siegwart, R., "StarlETH: A compliant quadrupedal robot for fast, efficient, and versa tile locomotion," in [*Proceedings of the International Conference on Climbing and Walking Robots (CLAWAR)*], (2012).

[27] Aoi, S., Sasaki, H., and Tsuchiya, K., "A Multilegged Modular Robot That Meanders: Investigation of Turning Maneuvers Using Its Inherent Dynamic Characteristics," *SIAM J. Appl. Dyn. Syst.* **6**, 348–377 (Jan. 2007).

[28] Blickhan, R., Seyfarth, A., Geyer, H., Grimmer, S., Wagner, H., and Günther, M., "Intelligence by mechanics.," *Philos. Trans. A. Math. Phys. Eng. Sci.* **365**, 199–220 (Jan. 2007).

[29] Burden, S., Clark, J. E., Weingarten, J. D., Komsuoglu, H., and Koditschek, D. E., "Heterogeneous Leg Stiffness and Roll in Dynamic Running," *IEEE Int.Conf. Robot. Autom.* , 4645–4652 (Apr. 2007).

[30] Full, R. J., Kubow, T., Schmitt, J., Holmes, P. J., and Koditschek, D. E., "Quantifying dynamic stability and maneuverability in legged locomotion.," *Integr. Comp. Biol.* **42**, 149–57 (Mar. 2002).

[31] Jindrich, D. L. and Full, R. J., "Many-legged maneuverability: dynamics of turning in hexapods," *The Journal of experimental biology* **202**(12), 1603–1623 (1999).

[32] Revzen, S. and Guckenheimer, J. M., "Finding the dimension of slow dynamics in a rhythmic system.," *J. R. Soc. Interface* **9**, 957–71 (May 2012).

[33] Spagna, J. C., Goldman, D. I., Lin, P.-C., Koditschek, D. E., and Full, R. J., "Distributed mechanical feedback in arthropods and robots simplifies control of rapid running on challenging terrain.," *Bioinspir. Biomim.* **2**, 9–18 (Mar. 2007).

[34] McClung, A. J., *Techniques for Dynamic Maneuvering of Hexapedal Legged Robots*, PhD thesis, Stanford University (2006).

[35] Kim, S., Clark, J. E., and Cutkosky, M. R., "iSprawl: Design and Tuning for High-speed Autonomous Open-loop Running," *Int. Jnl. Robot. Res.* **25**, 903–912 (Sept. 2006).