BILL-LEGS:
Low computation Emergent Gait System for Small Mobile Robots

William A. Lewinger, *Member, IEEE* Roger D. Quinn, *Member, IEEE*

Abstract—For almost two decades, Holk Cruse's leg coordination method has been used as a control basis for generating gaits in legged robots. His stick insect inspired method has been successfully implemented for a number of robots such as Robot I and Robot II, the TUM Walking Machine, Tarry II, and BILL-Ant-p. However, some engineers have had difficulties implementing the controller when trying to select robust mechanism influence weights that are immune to variations in starting pose and leg speed. Additionally, the coordination method can be overwhelming for low-computation capable microcontrollers preferred for small, untethered mobile robots.

The Biologically-Inspired Legged Locomotion-Low computation Emergent Gait System (BILL-LEGS) was developed as a solution to some of these issues. This method borrows heavily from Cruse's original design with some modifications that allow it to be implemented on small, autonomous legged robots using simple microcontrollers.

This paper describes the BILL-LEGS method and its performance during simulation. Additionally, data are presented that show its robustness to mechanism weight selection and its generation of stable gaits, independent of leg starting positions and leg movement speeds.

I. INTRODUCTION

INSECTS coordinate the motions of their legs into patterns within a continuum of metachronal gaits, as described by Wilson [17], to generate walking movements that propel them toward their goals. Decades of behavioral studies by Cruse and others into stick insect inter-leg coordination led to a set of mechanisms and a network commonly called "Cruse's method" that synthesize this continuum of insect gaits (Fig. 1) [1,2,4].

With Cruse's method, legs generate mechanism values that are weighted and applied as influences on neighboring legs. The legs receiving the combined influences of their neighbors can then have stance/swing and swing/stance transition points altered (adjusting step length and foot placement) to form a coordinated series of gaits that vary with body speed. This rule set has been used in numerous simulations and robots, such as Robot I [7], Robot II [8], the

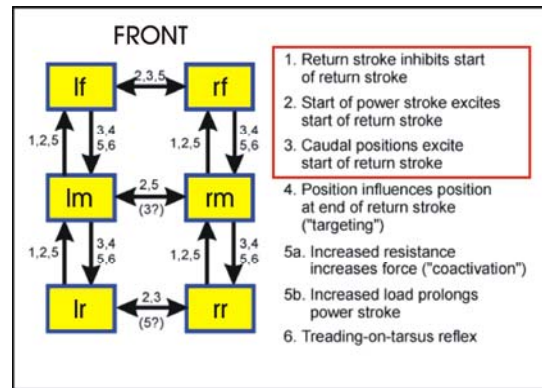TUM Walking Machine [16], Tarry II [9,2], and BILL-Ant-p [12].

Fig. 1. Mechanism connectivity network for Cruse's method of inter-leg coordination. Only the boxed mechanisms (1, 2, and 3) were used for Robot I, Robot II and BILL-Ant-p.

The Cruse method for leg coordination has numerous mechanisms, each with a weighted value of influence on neighboring legs. Robot I [7], Robot II [8], and BILL-Ant-p [12] each used a subset of these: mechanisms 1, 2, and 3. However, even with this subset, 8–12 unique mechanism weights needed to be calculated to allow smooth continuums of statically stable gaits to form. For Robot I and Robot II, mechanism weights were manually chosen. For BILL-Ant-p, a genetic algorithm was used to find values.

One of the difficulties in selecting mechanism weights is that the chosen values affect which gaits emerge, if at all, and how stable the gaits are [7]. While some of the mechanisms (i.e. mechanism 2) are less influential than others in creating a smooth continuum of insect gaits that vary with body speed, others (i.e. mechanism 3) are more crucial. There are also situations where certain values cause statically unstable postures that may not appear immediately, but emerge after many stepping cycles.

Espenschied [8] presented data that showed the robustness of Cruse's method when selecting mechanism weights (Fig. 2). It was shown that mechanism 2 was not very important to the formation of stable gaits, while mechanism 1 was somewhat important, and mechanism 3 was very important and the least robust to alteration.

The controller for BILL-Ant-p also used mechanisms 1, 2, and 3, but showed less robustness for these mechanisms to alteration (Fig. 3). It is believed that the axially-symmetric starting pose of the legs with respect to the sagittal plane may have generated fewer sets of mechanism weight
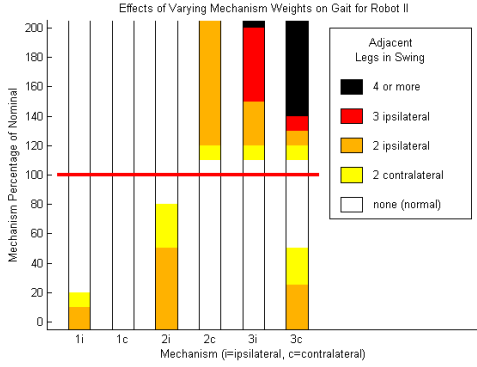
candidates.

Fig. 2. Immunity of leg coordination mechanism weights to variation in the generation of stable gaits for the Cruse method in Robot II. The white bands indicate mechanism weight values that generate stable gaits. The horizontal line at 100% represents the nominal mechanism weight values.
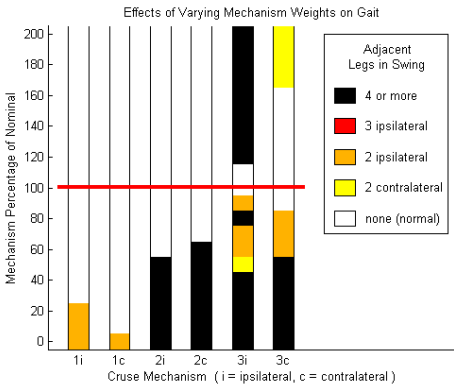

Fig. 3. Immunity of leg coordination mechanism weights to variation in the generation of stable gaits for the Cruse method in BILL-Ant-p. Note the smaller allowed variation of weights (smaller white spaces surrounding the horizontal line at 100%) to those used for Robot II (Fig. 2).

Further tests performed with BILL-Ant-p showed relatively small changes in starting pose and leg speed caused undesirable stepping patterns (Fig. 4). While the situation of two contralateral legs simultaneously in swing is seen in insects (e.g. in climbing [15]), this situation was undesirable for BILL-Ant-p. Since the center of mass in BILL-Ant-p is slightly forward of the middle Thoraco-Coxal (ThC) joints, the robot would fall forward if both front legs were in swing. Consequently, mechanism weights were chosen to not allow this situation for all gait patterns and body speeds.

II. BILL-LEGS METHOD

The BILL-LEGS method is very similar to Cruse's method for leg coordination in that it's a modular, distributed system in which neighboring legs influence one another by weighted mechanisms to form continuums of gaits. A key difference is that BILL-LEGS uses only two mechanisms and a total of two system-wide mechanism setpoint values to coordinate inter-leg movements (Fig. 5).

All legs use the same two setpoints, one for each mechanism; unique ipsilateral and contralateral values are not needed. Another major difference is that the legs influence themselves.
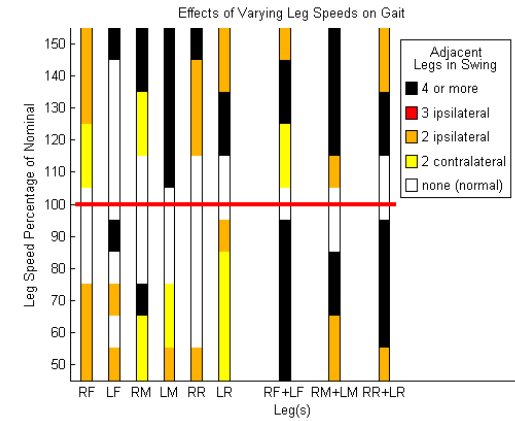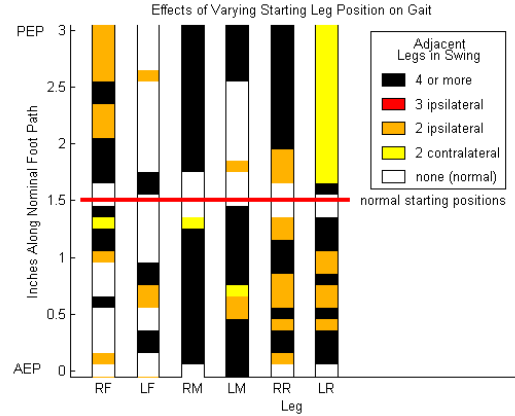

Fig. 4. The effects of varying individual starting leg positions (top) and leg movement speeds of individual legs and leg pairs (bottom) on stable gait generation for the Cruse method in BILL-Ant-p. The small white bands about the horizontal line at 100% indicate the lack of robustness to changes. Larger white bands would indicate more robustness.

It is important to mention that BILL-LEGS does not perform all of the functions of Cruse's method. The omission of mechanisms limits its use for behaviors such as "follow-the-leader" where caudal legs step on positions previously occupied by rostral legs. These mechanisms were removed since they are more suited to the stick insect's extremely sparse environment.

The first of two mechanisms is a fixed-level signal when a leg is in swing phase. The second is a ramp signal during stance that represents the percentage of the distance traveled from the intrinsic anterior extreme position (iAEP) to the intrinsic posterior extreme position (iPEP).

While in stance, each leg generates a positive signal between 0 and 1 (for processors with floating-point math) as it moves from the iAEP to the iPEP (mechanism 2). Positions beyond the iPEP generate signals larger than 1. When a leg is in swing phase, a fixed, positive value larger than the leg's entire range-of-motion (RoM) is used instead (1.1 times the total joint range of motion * 3). This value is chosen to be larger than any possible mechanism 2 value a

leg in stance could generate, regardless of its iAEP and iPEP positions, times the maximum number (3) of neighboring legs. Once all the mechanism values are generated, they are shared with orthogonally neighboring legs (Fig. 5).
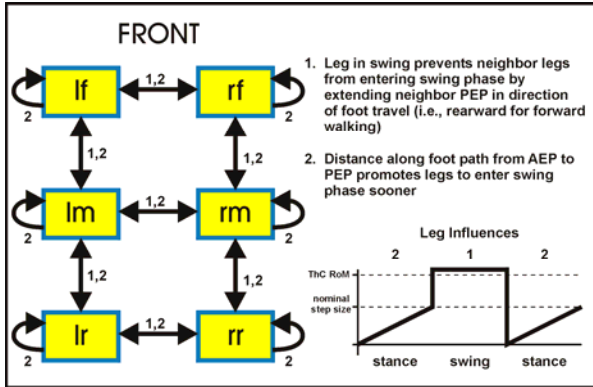

Fig. 5. Only two mechanisms are used for BILL-LEGS. They are equivalent to Cruse's mechanism 1 and mechanism 3 and influence each orthogonal neighbor bi-directionally. A key difference in BILL-LEGS is that the legs influence themselves as well as neighbors.

Net influence values are calculated for each leg in stance during each control cycle. The influence calculation begins with the positive influence of the current leg on itself (a difference from Cruse's method), and then subtracts the averaged influence of orthogonal neighbor legs.

$$stance\ influence = (iAEP - foot\ position) / foot\ path$$
$$swing\ influence = 3.3 \bullet RoM \quad\quad (1)$$
$$net\ influence = leg\ influence - \sum \frac{neighbor\ influences}{number\ of\ neighbors}$$

By using a swing phase influence weight greater than 3, the net influence is negative when at least one neighboring leg is in swing, so the BILL-LEGS mechanism 1 setpoint is 0. When the net influence is negative the PEP for the current leg is set beyond the extreme RoM position in the direction of leg travel (i.e., beyond the most rearward position physically reachable when the robot is walking forward). Since the leg cannot reach this position, it never meets the criteria to enter swing. If a neighboring leg in swing takes too long to begin its stance phase, the current leg will drag at its physical limit, although this rarely happens since the swing speed is at least twice the stance speed and the nominal step length is about half of the RoM.

If the net influence is greater than 0.70 (the nominal setpoint for BILL-LEGS mechanism 2), the PEP for the leg is set to its current position, thus initiating the swing phase immediately. This condition occurs when a leg is slightly farther along its foot path than its neighbors. Initiating swing early starts the following stance phase early as well, which minimizes the time neighboring legs need to wait before beginning their own swing phases.

Mechanism 2 setpoint values less than 60% of the step length produce irregular or "stuttering" gaits, while values greater than 80% produce gaits based solely on the starting

pose. Using a setpoint of 70% produced the best results.

$$PEP = \begin{cases} > RoM\ limit & if & influence < 0 \\ iPEP & if & 0 \leq influence < 0.70 \quad (2) \\ current\ position & if & influence \geq 0.70 \end{cases}$$

For integer-only processors, like small microcontrollers, the "percentage along the foot path" influence value is replaced by an integer, such as mm or cm along the foot path, or angle of the protraction/retraction joint. Legs in swing have an influence that is 3.3 • RoM truncated to the nearest integer. The net influence calculations are then performed similarly to those for the floating-point math processors shown in (1). The mechanism 2 setpoint is set to an integer value of approximately 0.70% of the distance from iAEP to iPEP; the mechanism 1 setpoint remains 0.

III. BILL-LEGS SIMULATION ENVIRONMENT

A simple simulation environment was created using MATLAB R2006b (The MathWorks, Inc.) that modeled a six leg, 2-DOF/leg robot. Legs were capable of protracting and retracting with a Thoraco-Coxal (ThC) joint, and had a second DOF that allowed them to be in either swing or stance. 9cm-long legs (representing the coxa, trochanter, and femur) were mounted perpendicularly to a central, 20cm-long thorax and had ranges-of-motion (RoM) of ±45 degrees. The measurements used were taken from the physical BILL-Ant-p robot. The tibia and foot segments were not used as they are typically oriented vertically and add no length to the leg when viewed from above. Swing speeds were set to 333deg/sec, which is the maximum speed of the servo motors used in the BILL-Ant-p ThC joints.

The simulator used all integer values (similar to a low-computation capable microcontroller) and measured leg movements as ThC angle with a nominal stance length of 50 degrees (±25 degrees perpendicular to the thorax). The BILL-LEGS mechanism 1 and 2 setpoints were chosen as 0 and 35 (70% of 50 degrees), respectively.

Because the simulator was developed as a single piece of software, each leg's calculations were performed sequentially; the actual robot uses distributed controllers that perform the calculations asynchronously in parallel.

The number of calculation cycles (duration of the simulation), starting and ending stance speeds (as a percentage of swing speed), and over how many calculation cycles a ramp-up or ramp-down of stance speed was to occur (if a speed change was specified for a given test) could be set at run time. The outputs of the simulator were several plots and two animations.

This environment also allowed independent setting of the iAEP and iPEP values, starting ThC angles (corresponding to starting leg positions), and joint actuator speeds for each leg. By entering different iAEP and iPEP values, the step lengths could be changed to create turning movements using a form of skid steering, where legs on the inside of the turn

moved slower and over shorter step lengths. While this is not how insects perform turning actions [6], it was all that could be accomplished with 2-DOF legs. It was demonstrated, however, that while the simulated foot trajectories differed from actual insect foot paths during turning, the stance duration was longer for outside legs than inside legs, similar to what Dürr and Ebeling showed [6].

IV. BILL-LEGS SIMULATION RESULTS

Several experiments were performed to test various aspects of the system. Important key points during the experiments were to thoroughly test if neighboring legs could simultaneously be in swing and how quickly insect gaits formed with a variety of starting poses, joint actuator speeds, and mechanism setpoints.

To test if neighboring legs could be in swing at the same time, the simulator was programmed to repeatedly run through trials of 5,000 calculation cycles (corresponding to approximately 28 steps for each leg). Stance speeds were ramped up from 0 to 50% of swing speed within the first 2,000 calculation cycles and held for the remaining cycles. Random ThC starting angles (within the entire range of motion) and random joint actuator speeds were also used during the trials. 10,000 trials were performed. At no time in any of the trials were neighboring legs simultaneously in their swing phase, showing that the controller produced statically stable gaits.

The next major aspect of testing was to see how gaits were generated as stance speeds were increased. For these trials, stance speed started at 0 and was increased to 50% of swing speed over the first 2,000 of the 5,000 calculation cycles during straight-line walking. The maximum stance speed of 50% swing speed was chosen as the point where the legs should be in an alternating tripod gait, according to work done by Kindermann and others [11].

The first series of gait tests were performed with identical joint actuator speeds for each leg. Three sets of starting ThC angles were used. The first set intentionally promoted a wave gait, the second began with all legs perpendicular to the thorax, and the third used randomly selected angles.

As seen in Fig. 6, the first test shows a continuum of gaits from wave to tetrapod to tripod. The second test, where the starting angles were perpendicular to the thorax, had all legs traveling rearward from the same points in the respective step lengths and at the same rates. Since the leg influences and swing/stance phase were computed for each leg beginning with the left-rear, a tripod was formed with the left-rear, right-middle, and left-front legs while the other legs had their PEPs extended and remained in stance. As soon as the first tripod of legs completed their swing phases, the remaining legs entered swing. Because of the starting positions of the legs, the wave and quadruped gaits were not seen for this test.

The bottom plot of Fig. 6 shows a similar test with random ThC starting angles. Note how the seemingly disjointed steps in the beginning become an orderly tripod gait as stance speed increased. A total of 10,000 trials were performed using random ThC starting angles; all trials produced statically stable results.
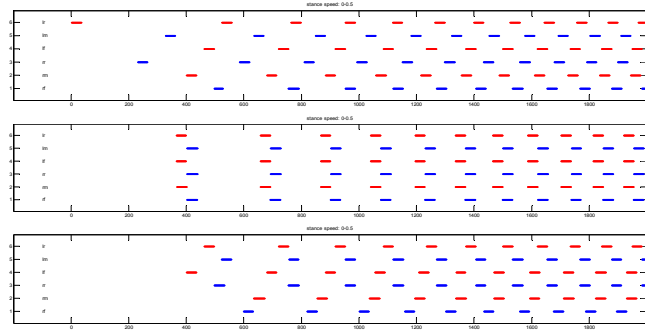

Fig. 6. Stance speed acceleration from 0–50% of swing speed with identical joint actuator speeds, and starting ThC angles (relative to a Cartesian plane) listed in the table below:

		lr: 115	lm: 95	lf: 75
(a)		rr: 255	rm: 275	rf: 295
(b)		lr: 90	lm: 90	lf: 90
		rr: 270	rm: 270	rf: 270
(c)		lr: 75	lm: 64	lf: 85
		rr: 286	rm: 313	rf: 312

The top plot shows a continuum of gaits forming from wave, through tetrapod, to tripod. Due to the starting pose of the legs, the middle plot shows only a tripod gait forming. The bottom plot shows an irregular tripod gait forming after only a few steps, then becoming a more natural tripod gait.

Note: Lines in the swing/stance plots indicate the swing phase. Leg phases are shown in order from top to bottom as LR, LM, LF, RR, RM, and RF.

The next series of tests on gait formation used the same starting ThC joint angles as the first test of the previous gait formation trials (angles that promoted an initial wave gait), but allowed the joint actuator speed (for both stance and swing) to vary from ±5% to ±25% of nominal. Joint actuator speeds were randomized at the beginning of each of 10,000 trials per speed variance and maintained for the duration of each test. All trials used straight-line walking with a ramp up of baseline stance speed (stance speed before randomization) from 0 to 50% of swing speed. Result samples are shown in Fig. 7.

A continuum of gaits was seen and the standard alternating tripod gait was eventually formed in each trial up to ±15% variation in actuator speed. The final gaits for the ±20% and ±25% trials resembled alternating tripods, but were not as well-formed as in previous tests.

Also, the slow right-rear joint actuator in Fig. 7b can be identified by the long stance and swing phases. The slow speed led to missing every other swing phase cycle with the other legs in its tripod, the left-middle and right-front legs. The other tripod (left-rear, right-middle, and left-front legs) with similarly-matched actuator speeds maintained their synchronized stance and swing phases despite the less-coordinated actions of the other legs.

Additional tests were performed with the stance speeds

increasing in phases: 0-10%, 10-20%, 20-30%, 30-40%, and 40-50% of the swing speed, with each phase lasting 10,000 cycles (8,000 to accelerate and 2,000 at the maximum speed for the phase). These slow acceleration tests were conducted to ensure gaits had more than sufficient time to stabilize before increasing the speed. The tests showed similar results to previous tests, indicating the continuum of gaits produced were stable and not transitory.
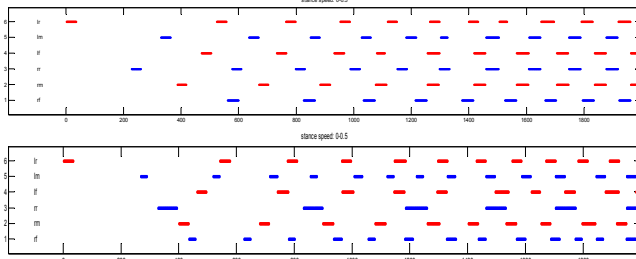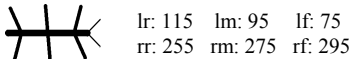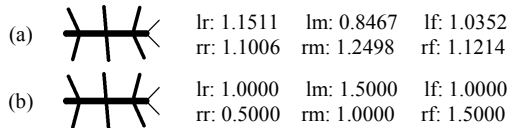

Fig. 7. Six tests with stance speed acceleration from 0–50% of swing speed, and fixed starting ThC angles (relative to a Cartesian plane) listed in the tables below:

lr: 115   lm: 95   lf: 75
rr: 255   rm: 275   rf: 295

Five tests used randomized actuator speeds (1.00±5%, ±10%, ±15%, ±20%, and ±25%) and a sixth test used hand-selected speed values. The results of test 3 (±15%) and test 6 (hand-picked) are shown.

Joint actuator speed values

(a)
lr: 1.1511   lm: 0.8467   lf: 1.0352
rr: 1.1006   rm: 1.2498   rf: 1.1214

(b)
lr: 1.0000   lm: 1.5000   lf: 1.0000
rr: 0.5000   rm: 1.0000   rf: 1.5000

Note: lines in the swing/stance plots indicate the swing phase. Leg phases are shown in order from top to bottom as LR, LM, LF, RR, RM, and RF.

It should be noted that not all gaits were observed with variations on starting poses and leg movement speeds as the baseline stance speed increased from 0 − 50% of swing speed. For ideal conditions, the wave, tetrapod, and tripod gaits were seen. In different scenarios, however, only a subset of gaits emerged, such as tetrapod and tripod, or only tripod. These results are not surprising in light of similar findings by Cruse *et al*. [2]:

Actually very different step patterns can be observed e.g. after a brief disturbance of the movement of a single leg or when animals start walking from different leg configurations [10,5]. Insect gaits may therefore better be described by the term "free gaits" [14]. The usually observed tripod or tetrapod patterns represent limit cycle solutions that are only apparent in undisturbed situations [3].

It's important to clarify that while the observed gait progression varied with starting and operating conditions, there were no statically unstable gaits generated.

After performing the gait formation experiments a series of turning trials was performed. These trials tested gait stability while adjusting iPEP values of the left legs to be closer to the iAEP values, thus shortening the foot path. Since leg speed is a function of stance length in the simulation, legs with short foot paths (inside legs) move more slowly than those with longer foot paths (outside legs).

Three tests were performed with stance speeds fixed at 50% of swing speed (no ramp-up period) and no randomized speed adjustments (Fig. 8). Starting ThC angles were set perpendicular to the thorax for each leg during all the tests.
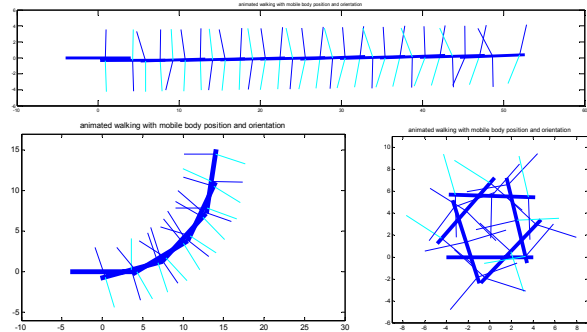

Fig. 8. Composite images of the body and legs with fixed 50 degree foot paths for right legs, and decreasing foot path lengths for left legs.
(a) left: 50 degrees   right: 50 degrees
(b) left: 30 degrees   right: 50 degrees
(c) left: 5 degrees   right: 50 degrees

The straight-line walking test (Fig. 8a) used 50 degree stance lengths for all legs. The left arc test (Fig. 8b) maintained the stance length for the right-side legs, but shortened the left-side legs to 30 degrees. A 90 degree turn had a turning radius of about 35.6cm (14.0in). Reducing the left-side stance lengths to 5 degrees created a tight left turn (Fig. 8c) with a radius of approximately 9.0cm (3.5in).

Fig. 9 shows a series of swing/stance plots for each of the three turning trials. The left-side legs have progressively smaller swing phases due to the shortening of the foot paths for each successive trial, but longer stance phases due to the slower walking speeds of the inside legs.
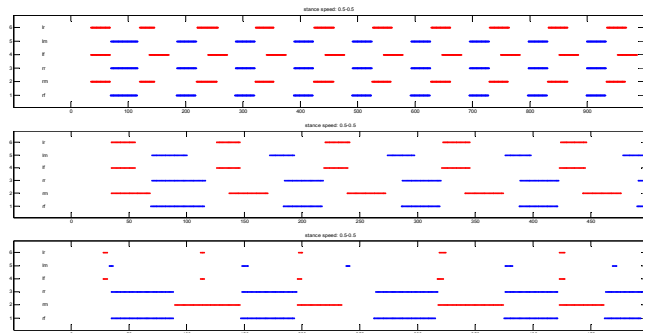

Fig. 9. Swing/stance plots of the turning trials with foot path lengths as follows:
(a) left: 50 degrees   right: 50 degrees
(b) left: 30 degrees   right: 50 degrees
(c) left: 5 degrees   right: 50 degrees

Note: lines in the swing/stance plots indicate the swing phase. Leg phases are shown in order from top to bottom as LR, LM, LF, RR, RM, and RF.

One final series of tests was performed to further determine the robustness of the BILL-LEGS method to changes in mechanism setpoint values, starting pose, and joint actuator speed. As shown in Fig. 10, BILL-LEGS is extremely robust to variations on system parameters, starting

leg positions, and joint actuator speeds. While the types of gaits that were generated varied as the setpoints changed, all of the gaits were statically stable. It was observed, however, that the mechanism 1 setpoint needed to be ≤ 0 to be effective (Fig. 10, top). When the setpoint was >0, the legs moved to the iPEPs and remained there without initiating a swing phase.
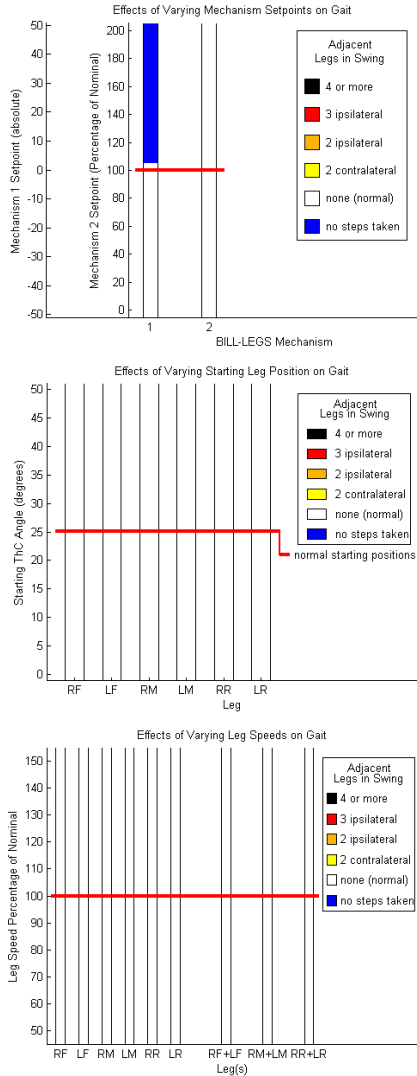

Fig. 10. Robustness of BILL-LEGS to variations in mechanism setpoints, starting leg positions, and leg movement speeds. Varying any parameter results in statically stable gaits, with the exception of the mechanism 1 threshold, which is limited to values ≤0. Threshold values >0 prevent leg transitions from stance to swing phase, and the legs remain standing at the PEP locations.

V. CONCLUSIONS

The goal of this project was to create a robust, simple, low-computation method for coordinating legs of a hexapod robot to generate a continuum of statically stable gaits. By using only two mechanisms and two system-wide mechanism setpoints, BILL-LEGS coordinates leg movements such that statically stable gaits are generated independent of starting leg positions or leg movement

speeds. This method has also been shown to be robust to variations in mechanism setpoint values. Due to the extremely simple algorithms used in BILL-LEGS, it is ideally suited for small, legged robots with low-computation capable microcontrollers. By combining this method with the SCASM controller [13] a small, fully autonomous legged robot can be controlled using simple microcontrollers.

REFERENCES

[1] H. Cruse, "What Mechanisms Coordinate Leg Movement in Walking Arthropods?" in *Trends in Neurosciences*, vol. 13, 1990, pp. 15–21.

[2] H. Cruse, V. Duur, J. Schmitz, and A. Schneider, "Control of hexapod walking in biological systems," in *Proceedings of the 2nd International Symposium on Adaptive Motion of Animals and Machines*, Kyoto, Japan, March 4-8, 2003.

[3] G.S. Cymbalyuk, R.M. Borisyuk, U. Müller-Wilm, and H. Cruse, "Oscillatory networks controlling six-legged locomotion," in *Neural Networks*, 11, 1449–1460, 1998.

[4] J. Dean, "A model of leg coordination in the stick insect, Carausius morosus; I. Geometrical consideration of contralateral and ipsilateral coordination mechanisms between two adjacent legs," in *Biological Cybernetics*, vol. 64, pp. 393–402, 1991.

[5] J. Dean and G. Wendler, "Stick insect locomotion on a wheel: Patterns of stopping and starting," *J. exp. Biol.*, 110, 203–216, 1984.

[6] V. Dürr and W. Ebeling, "The behavioural transition from straight to curve walking: kinetics of leg movement parameters and the initiation of turning," in *The Journal of Experimental Biology*, vol. 208, pp. 2237–2252, 2005.

[7] K.S. Espenschied, R.D. Quinn, H.J. Chiel, and R.D. Beer, "Leg Coordination Mechanisms in Stick Insect Applied to Hexapod Robot Locomotion," in *Adaptive Behavior*, vol. 1, no. 4, 455–468, 1993.

[8] K.S. Espenschied, R.D. Quinn, H.J. Chiel, and R.D. Beer, "Biologically-Based Distributed Control and Local Reflexes Improve Rough Terrain Locomotion in a Hexapod Robot," Robotics and Autonomous Systems, Vol. 18, pp. 59-64, 1996.

[9] M. Frik, M. Guddat, M. Karatas, and C.D. Losch, "A novel approach to autonomous control of walking machines," in *Proceedings of the 2nd International Conference on Climbing and Walking Robots* (CLAWAR'99), pp 333–342, Portsmouth, UK, Sept. 13–15, 1999.

[10] D. Graham, "A behavioural analysis of the temporal organisation of walking movements in the 1st instar and adult stick insect," in *J. comp. Physiol.*, 18, 23–52, 1972.

[11] T. Kindermann, H. Cruse, and J. Dean, "A biologically motivated controller for a six-legged walking system," in *Proc. of the 24th Annual Conference of the IEEE Industrial Electronics Society* (IECON 98), vol. 4, pp. 2168-2173, Aachen, Germany, Sept. 1998.

[12] W.A. Lewinger, M.S. Branicky and R.D. Quinn, "Insect-inspired, actively compliant robotic hexapod," in *Proceedings of the International Conference on Climbing and Walking Robots* (CLAWAR'05), pp. 65–72, London, UK, Sept. 13–15, 2005.

[13] W.A. Lewinger, B.L. Rutter, M. Blümel, A. Büschges and R.D. Quinn, "Sensory Coupled Action Switching Modules generate robust, adaptive stepping in legged robots," in *Proceedings of the International Conference on Climbing and Walking Robots* (CLAWAR'06), pp. 661–671, Brussels, Belgium, Sept 12–14, 2006.

[14] R.B. McGhee and G.I. Iswandhi, "Adaptive locomotion of a multilegged robot over rough terrain," in *IEEE Transactions on Systems, Man, and Cybernetics* (SMC-9), (4), 176–182, 1979.

[15] J.T. Watson, R.E. Ritzmann, "Leg Kinematics and Muscle Activity during Treadmill Running in the Cockroach", *Blaberus discoidalis:* I. Slow running," in *J. comp. physiology,* Vol. 182: 11-22, 1998

[16] H.-J. Weidermann, F. Pfeiffer, J. Eltze, "The six-legged TUM walking robot," in *Proceedings of IEEE/RSJ/GI International Conference of Intelligent Robots and Systems* (IROS'94), vol. 2, pp. 1026–1033, Munich Germany, Sept. 12–16, 1994.

[17] D. M. Wilson, "Insect Walking," in *Annual Review of Entomology*, vol. 11, pp. 103–122, 1966.