2007 IEEE International Conference on
Robotics and Automation
Roma, Italy, 10-14 April 2007

A Biologically Inspired Approach to the Coordination of Hexapedal Gait

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Abstract— **This paper presents a method for the control of locomotion in a robot hexapod. The approach is based on the WalkNet structure, which in turn is based on the neural control structure of the insect *Carausius morosus*. Though the WalkNet structure has been shown to function well in kinematic (i.e., non-dynamic) simulations, the authors found that the approach to coordinated control of hexapedal locomotion entailed several significant problems when simulated in the presence of dynamic effects, including gravitational effects, inertial dynamics, and ground contact dynamics. As such, the authors propose several variations on the WalkNet structure that provides stable and robust locomotion in the presence of dynamics, while still maintaining the attributes of WalkNet coordinated control, including self-selection of gait and associated emergent behaviors. The approach is simulated in the presence of dynamics and shown to provide stable gait with emergent characteristics.**

I. INTRODUCTION

MANY research groups have developed approaches for the control of locomotion in hexapedal walking robots. The motivation to pursue this kind of locomotion rather than any other is that the hexapedal platform is by its physical nature extremely stable. The two principle gaits of this kind of walker, the tripod and tetrapod gaits, are both statically stable, since the hexapod maintains at least three points of ground contact at all time, which eliminates the need for active balancing in such platforms. Additionally, since the hexapod has redundant legs compared to the also naturally stable quadruped walker, it is theoretically possible for this sort of vehicle to be able to continue operation in the event of disabled limbs.

The various approaches for the control of locomotion in hexapods (and other multipedal robots) can be roughly categorized into three categories, which include central pattern generation approaches, finite state approaches, and coordination-based approaches. In the central pattern generation approaches, a gait is pre-selected by the designer and a central pattern generator is used that provides each leg with a trajectory signal. This signal corresponds to the solely internal representation of the robot's desired walking motion. Most approaches to locomotion in hexapedal walking devices follow this paradigm, as represented by the work of Lee and Lee [1], Zielinska et al. [2], Clark et al.[3], and others. Unlike the central pattern approaches, the finite-state approaches incorporate a set of conditions that place the robot into one of several states, as determined by a predetermined rule set for various types of environmental interaction (i.e., stair climbing, walking over flat terrain, etc.). Examples of this work include that of Tanaka and Matoba [4], Saranli et al. [5], and others.

The third major category, coordination-based approaches, is one in which the gait is not statically specified, but in which it is an emergent behavior resulting from some sort of coordination system. This type of system is theoretically able to more easily traverse arbitrary and possible hostile terrain since, as Klavins et al. [6] point out, the difference between the central pattern generator approach and that of the coordination system is akin to the difference between open-loop and closed-loop control.

This kind of approach has had some following, including the works of Chiel and Quinn et al. [7-8], Calvitti and Beer [9], Svinin et al. [10], Pfeiffer et al. [11], and others.

Cruse et al. [12-13] thoroughly investigated the neural control structure utilized for control of locomotion in the stick insect *Carausius morosus*. Specifically, by sequentially and selectively isolating various components of the insect's neural circuitry and by utilizing microelectrodes to measure neural activity during various phases of locomotion, Cruse et al. in essence "reverse-engineered" the neural circuitry of the *Carausius morosus*. Based on their investigations, they proposed a system of interconnected neural networks (collectively termed WalkNet) that emulates the circuitry that coordinates locomotion in the insect. As described subsequently, one of the interesting aspects of WalkNet, one that is patterned directly after the biological system, is the use of positive feedback (i.e., unstable feedback) in the stance phase of locomotion. Cruse et al. further demonstrated the promise of their approach via a series of simulations. One significant shortcoming of their validation, however, is that their simulations did not consider gravitational effects, inertial dynamics, or contact dynamics between the legs and the ground. In the case of a stick insect, one can argue that such (inertial) dynamics are not significant. At the scale of a typical hexapedal robot, however, such effects are significant, and have a significant bearing on the stability of a closed-loop system. In fact, as discovered by the authors, WalkNet (as presented by Cruse et al.) does not provide stable locomotion in the presence of dynamic effects. Motivated by this issue, the authors

Manuscript received September 15, 2006. This work was supported in part by the NSF Engineering Research Center for Compact and Efficient Fluid Power.

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propose a modified version of WalkNet that is based on its biological paradigm, but that provides stable locomotion in the presence of dynamics, while still enabling the significant benefits (i.e., self-selecting, robust, emergent behavior) of the WalkNet approach.

II. SYNOPSIS OF WALKNET

Cruse's neural network that achieves synthetic stick insect walking consists of three main subsystems, namely the swing net (which generates a leg's trajectory during swing phase), the stance net (which does the same for the stance phase), and the selector net (which decides for each leg which of the two trajectories to use).

The swing net is a neural network that has been trained using data from in vivo motion measurements of the stick insect, the results of which are subsequently massaged using a non-linear multiplier and a bias input so as to very closely mimic the swing trajectory of the animal.

For stance, Cruse propounds the idea that positive feedback of joint velocity can be used along with a few modifications to reliably and simply generate a stance trajectory. That is, if one of the important functions of the stance phase is to propel the body forward, such propulsion can be achieved (and apparently may be achieved in the stick insect) by using positive feedback in the thoracic-coxal (α) and femur-tibia (γ) joints, which simply push back against the ground while in contact with it.

One of the most significant benefits to the method proposed by Cruse is that, rather than use a central pattern generator as many hexpedal robots do, the gait is evolved due to the fact that each legs has the capacity to independently choose whether to execute a swing or a stance motion by following a set of simple rules. These rules are enumerated as six "coordinating influences" by Cruse and are implemented in WalkNet as the selector net subsystem. These coordinating influences are summarized in Fig. 1, which is reprinted from [13].

These influences work primarily by altering the "posterior extreme position," or the leg "point-of-no-return" position, beyond which a leg will transition from a stance phase motion into a swing phase motion. The end of swing phase is detected by sensing a ground impact. The selector net relies on these coordinating influences to evolve a stable walking gait.

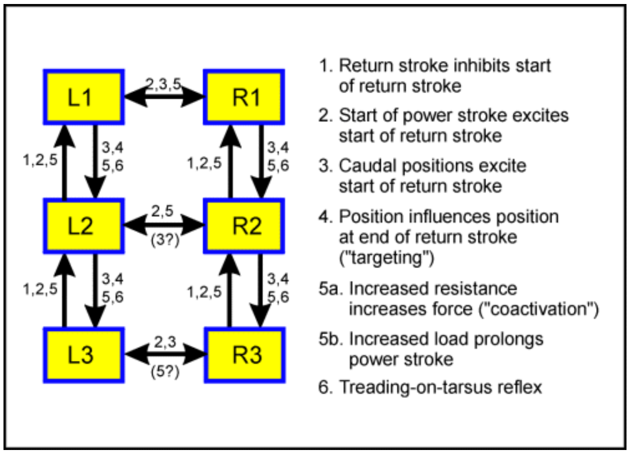

Fig. 1. Coordinating influences of WalkNet's selector net.

Another interesting aspect of the WalkNet structure is that both the swing and stance trajectory generators generate joint velocity commands rather than joint position commands in contrast to traditional robot controllers which in general are structured in terms of desired position trajectories. Note that biology's use of velocity based control is quite sensible, since the main objective of locomotion is to keep the body moving forward at a desired rate of speed. Velocity control is also generally simpler and more stable than position control, since velocity control in the presence of inertial dynamics generally involves only a single integration from (actuator) force.

III. PROBLEMS WITH WALKNET FOR ROBOT LOCOMOTION

As previously indicated, some difficulties exist with the realization of WalkNet in a hexapedal robot. The most significant is that no mechanism is described in WalkNet that maintains stability in the lateral direction, which is particularly significant in the presence of dynamic effects. Specifically, since WalkNet is by its nature a joint-level control approach (i.e., operates in the joint space rather than in the task space), the unstable behavior generated in the joint space by the use of positive feedback during stance phase may propel the body forward, but since the joint angles generally show up in all task space directions, the (intentionally) unstable behavior also propels the body laterally, which results in falling to the side. One could apply this notion of positive feedback in the task space and separate the forward and lateral dynamics (i.e., positive feedback in the forward direction, negative feedback in the lateral direction), but such an approach requires task space control, which in turn sacrifices much of the biologically inspired paradigm, and with it many of the most significant assets, such as emergent behavior and self-selected gait patterns. Additionally, the positive feedback concept relies on each stance leg remaining in contact with ground during the entire stance phase, which cannot be guaranteed in a real world trial. For example, a slippery substrate or a loose substrate that falls away as force is applied may cause the leg to lose contact with the ground. Once the stabilizing influence of the ground is no longer present, the positive feedback generates exponentially increasing velocity and hence an undesirable stance response.

IV. PROPOSED WALKING ALGORITHM

A block diagram of the proposed approach is shown in Fig. 2. The portion of the block diagram most integral to the proposed approach is enclosed by the dashed box and labeled "Trajectory Generation." The structure of this subsystem is based largely on that of the Cruse system in that there are independent blocks that generate the swing and stance trajectories and a third block that chooses which of the two trajectories to use based on the state of an individual leg and those of the neighboring legs. Unlike Cruse's system, however, the swing and stance phases are calculated through mathematical formulations, as subsequently described, rather than by neural networks.

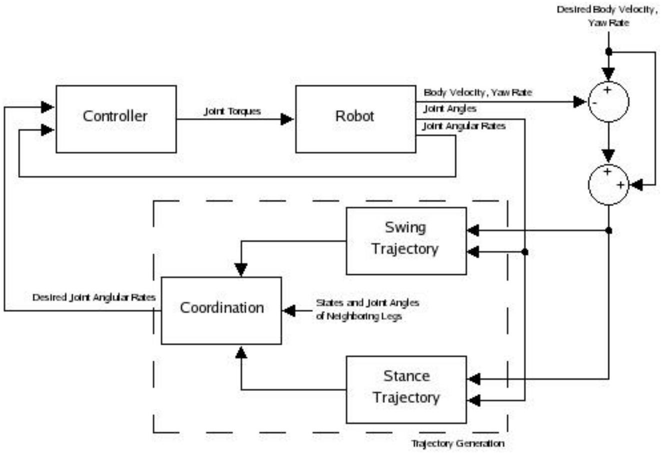

Fig. 2. Block diagram of proposed gait control structure.

A. Stance Phase

The stance trajectory is conceptually defined as being able to simultaneously meet the following criteria. First, the trajectory must cause the body to follow some desired linear and angular velocities (i.e., the desired inputs into the system are the desired linear and angular (or yaw) velocities of the body center of mass). This selection of inputs will allow the vehicle to be commanded in the same manner in which one is accustomed to driving an automobile. This criterion then consists of describing a straight line path of the foot parallel to the body axis with velocity equal to the desired body linear velocity. This path is then modulated using the desired angular velocity and the instantaneous distance from the body center of mass to the end point of each leg. Note that it is also possible to supply a desired lateral linear velocity to allow the vehicle to side-step or walk crabwise, although this is not included in the present implementation.

Secondly, the stance trajectory should maintain the robot body at some constant (vertical) distance from the ground, duplicating the function of the "height net" block in the WalkNet structure. Fundamentally, this amounts to a virtual suspension system with function and performance similar to that of a wheeled vehicle. However, the stiffness of the virtual spring in this system will vary depending on how many of the legs are in contact with the ground at a given time. In order to use this criterion, a desired height is required to simulate the free length of the virtual spring. Currently, this height is selected as some suitable constant, but could vary continuously if necessary or desired.

Finally, a third stance phase criterion keeps the robot body from falling laterally to one side by serving as a feedback loop that performs error correction in the lateral direction, a feature which does not appear to be present in WalkNet. The addition of this criterion has the added effect of maintaining the robot's heading more accurately than solely through the yaw rate feedback loop.

B. Swing Phase

The swing trajectory block takes the current position of an individual leg and calculates a set of joint angular velocities that causes the foot of that leg to follow a parabolic trajectory in the sagittal plane. Two important features govern the character of this trajectory. The first feature is that the expected foot-ground impact point must be selected in order to maximize the "sure-footedness" of the vehicle. This is a declaration of the inclusion of the fourth Cruse coordination influence or the so-called "targeting influence." The idea behind this influence is that if the next rostral (when walking forward) leg has a satisfactory foothold, then placing a foot near its rostral foot will also result in a satisfactory foothold and the avoidance of a possible gap. Of course, some allowance needs to be made in order to keep the two legs from contacting. This is done by locating the target end-point of the swing movement some small distance behind the current position of the next rostral foot.

For the most rostral (i.e., most forward) legs, no such information exists, so the target points are chosen arbitrarily. This raises a concern pertaining to the behavior of the leg if intersection with the ground does not occur as expected. Should this occur, following the described parabolic trajectory is problematic because the leg will eventually reach a singular configuration. While this scenario is not possible in the current simulation because of the simple environment chosen, Durr [14] has conducted research extending that of Cruse and has identified a stereotypical searching algorithm that the stick insect executes in order to find a foothold. It is expected that continuing the biological analogy by using this method will result in successes similar to those described by Durr. Note finally that use of velocity rather than position control will in general result in less precision in foot placement than position control. However, reasonable proximity can be attained by allowing the trajectory generator to use feedback information from the current leg position when determining desired joint velocities.

The second feature that governs the nature of the swing trajectory is that the vertical velocity when the foot is expected to impact ground should be kept small in order to minimize impact forces and the ensuing rapid body height fluctuations (i.e., vibrations), which dictates that the parabolic trajectory be "shallow." Note that a shallow trajectory will in general increase the likelihood of a possible collision between a leg and some environmental obstruction. However, this possibility is not of great concern since the current simulation is focused solely on level walking in an ideal environment and also since Cruse describes methods observed in the stick insect to recover from such collisions.

From the above criteria, this parabolic trajectory is constructed so that it passes through two points: the leg's current position and the desired target. Also, it is desired to pass through some maximum height and in the absence of additional constraints, we force this maximum to occur at the transverse plane passing through the leg's basal joint. Finally, since velocities are to be the result, the parabolas are mathematically formulated as in (1) and (2). Here, x is the body axial direction with positive values being rostrally directed, z is the vertical axis with positive values being upward, y is the lateral axis with positive values being anatomically sinister (left), and k_1 and k_2 are constants.

$$\begin{aligned} \dot{x} &= k_1 \cdot v_{body,des} \\ \dot{y} &= k_2\left(y_{target} - y\right) \end{aligned} \tag{1}$$

$$\begin{aligned} \dot{z} &= 2 \cdot A \cdot x \cdot \dot{x} \\ A &= \frac{z - z_{\max}}{x^2}, x < 0, x \geq x_{target} \\ A &= \frac{z_{target} - z}{x_{target}^2 - x^2}, 0 \leq x < x_{target} \end{aligned} \tag{2}$$

C. Leg Coordination

The coordination block shown in Fig. 2 is implemented using the set of coordination influences from the work of Cruse et al. Currently, influences 5 and 6 are not in the present implementation, as they relate to non-ideal environments, which have not been considered in the work herein, although will be integrated in future work. Additionally, the authors have found that allowing influence 1 to act on all neighboring legs (non-diagonal) rather than caudal-only causes the vehicle to easily and stably change speeds, since such an allowance appears to evolve gaits more quickly than without. Finally, the gains used in the modified version presented herein use a different set of gains than those utilized in Cruse's WalkNet, and in particular were tuned in order to achieve a satisfactory performance for the robot dynamics that include inertial, gravitational, and ground contact effects.

V. SIMULATION

The previously described walking algorithm has been implemented in a software simulation that includes robot dynamics and simulates ground contact using the open source Open Dynamics Engine library. Ground contact is modeled using the collision detection features built into the library and essentially amounts to a spring-damper connection between colliding bodies. For the purpose of collision detection, the ground is modeled as an infinite flat plane and the leg segments as spherically capped cylinders. The torque control at each joint is simulated as a local proportional velocity control loop, wherein the generated torque is proportional to the error in joint velocity. Actuator dynamics were not simulated at this point, since they were assumed to be fast relative to the frequencies of locomotion, although joint torques were saturated at representative levels. Body and leg segments are considered to be point masses with values as documented in Table 1 and defined as shown in Fig. 4, reprinted from [13].

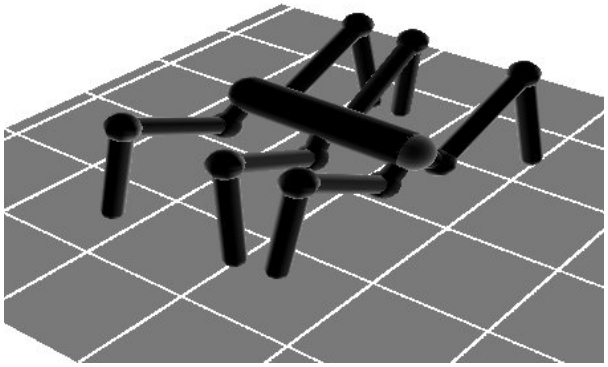

Fig. 3. Sample screenshot of simulation as run.

TABLE I
SUMMARY OF BODY SEGMENT VALUES

Segment	Mass (kg)	Length (cm)
Coxa	0.36	5
Femur	0.28	15
Tibia	0.28	15
Thorax	2.3	20

Information used by the walking algorithm is limited to that which would be available via the sensors on the robot, namely the individual leg joint angular positions, the body linear and angular velocities, and the axial load on the distal leg segments.

Using the described walking method, the vehicle is able to conduct forward walking with and without simultaneous turning and is capable of starting from and coming to a stop. Also, the simulation permits the user to continuously change the input linear and angular velocities. Note that backwards walking and turning in place are not currently implemented, though the method does not preclude the possibility of these features, both of which are topics of future work.

The simulated vehicle is indicative of an in-progress physical robot which the authors are currently designing.

The legs of the simulated system and the eventual physical system are modeled after the stick insect's legs in terms of joint orientation and relative leg segment lengths. A sketch of the insect's limb is shown below, and segment lengths used are listed along with their projected mass in Table 1.

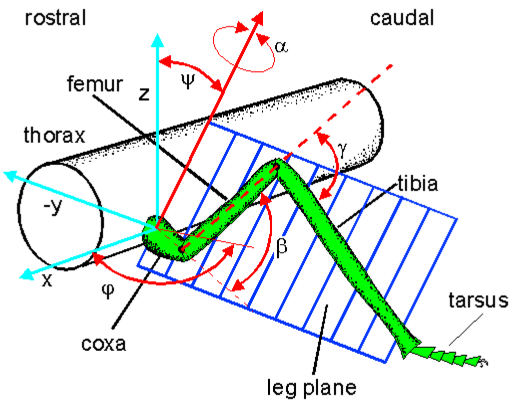

Fig. 4. Definition of leg geometry using biological inspiration.

In the current simulation, ψ is set to 45° and φ to 90°. Ongoing work is determining optimal values for these two angles that will evenly distribute joint power contributions, and that will also promote gait stability. The other three angles shown in the diagram are those which are actuated and controlled to perform the described leg motions.

VI. RESULTS

The emergent coordination between the legs can be seen in Fig. 5, which depicts the position along the body axis of all feet relative to their individual hip locations. The result is the stereotypical tripod gait with a phase separation of approximately .4 seconds.

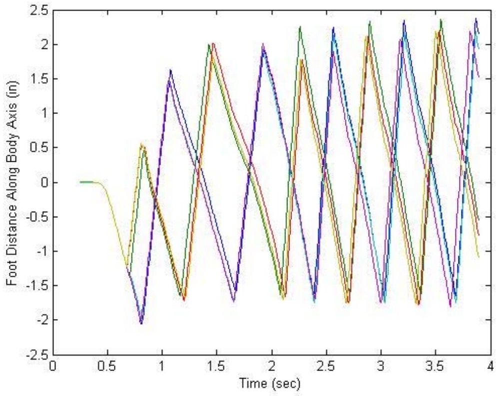

Fig. 5. Emergence of tripod gait using coordination influences.

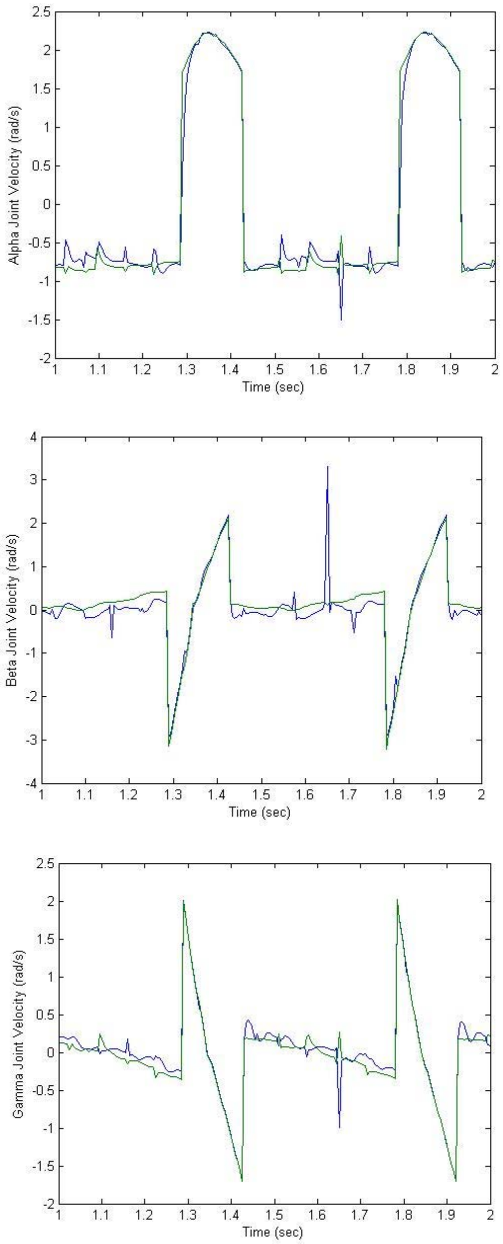

Fig. 6. Joint velocity tracking for all joints in one leg.

The joint level velocity commands, and resultant velocity tracking is shown in Fig. 6 for the three joints of one leg. From these plots, one can observe that the velocity tracks easily during swing motions, while the higher impedance of the ground interaction during stance motions creates a sufficient disturbance to generate noticeable tracking error.

A time history of an individual leg's trajectory in the sagittal plane is shown in Fig. 7, which shows the development of a single leg's trajectory over time as the coordinating influences act to shorten or lengthen the duration of the stance phase of the leg as well as showing the character of the parabolic swing phase trajectory.

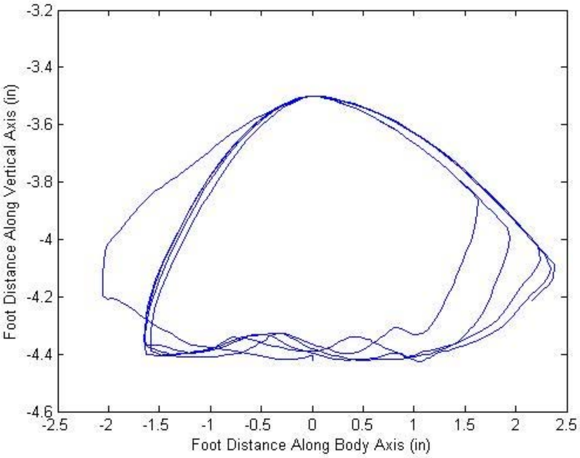

Fig. 7. Single foot trajectory in sagittal plane evolved over time.

When a non-zero desired yaw rate is introduced to the system, as in Fig. 8, the resulting gait pattern becomes somewhat chaotic. Here, the yaw command is made non-zero starting at approximately 5.7 seconds. Thereafter, the well-ordered gait pattern dissociates into a seemingly disordered, but still stable and functional gait pattern. Although this gait is not able to be classified as either a standard tripod or tetrapod gait, it is able to propel the robot along while reasonably following the desired linear and angular velocities.

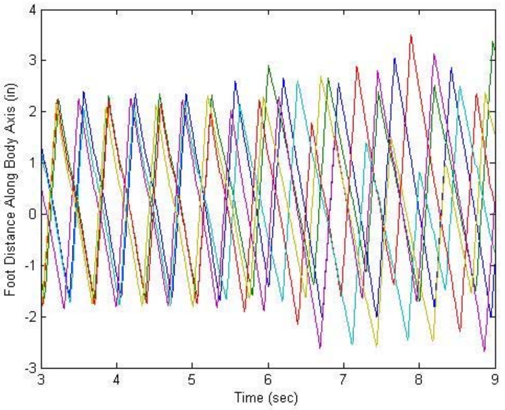

Fig. 8. Gait time history with non-zero yaw command introduced at ~5.7s.

VII. CONCLUSIONS

The foundation laid by Cruse with respect to emergent stable walking gaits allows rapid development of a complete walking algorithm. Using simple trajectory generation and joint control combined with the coordinating influences as described, a dynamic simulation has been implemented which can guide a hexapedal robot through arbitrary curvilinear paths.

On-going work includes the implementation of purely lateral motion, turning-in-place, and walking backwards. Additionally future work includes testing the approach with non-ideal environments, especially those which include uneven (rocky) terrain and slippery substrates.

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