Proceedings of IMECE'04
2004 ASME International Mechanical Engineering Congress and Exposition
Anaheim, California, USA, November 15-17, 2004

IMECE2004-61150

RAPID MANEUVERING OF A BIOLOGICALLY INSPIRED HEXAPEDAL ROBOT

Arthur J. McClung
Mark R.Cutkosky
Department of Mechanical Engineering
Stanford University
Stanford, California 94305
Email: amcclung@stanford.edu

Jorge G. Cham
Department of Mechanical Engineering
California Institute of Technology
Pasadena, California 91125

ABSTRACT

In dynamic running hexapods, stable and rapid turns can be achieved by small changes in the nominal configuration of the system used for straight-ahead running. Such changes in configuration, or "shape," alter the direction of the ground reaction forces and result in a high rate of change in heading and orientation. In this paper, we explore strategies for rapid maneuverability of a hexapedal running robot, taking further inspiration from its exemplar, the cockroach. Through simulation and experiments, we show that a one-parameter control input, or turn factor, *can be used to coordinate changes in the multi-dimensional configuration space of the robot for efficient turning up to 4 rad/s. This turn factor is used in the characterization of turning dynamics via system identification techniques.*

INTRODUCTION

Rapid and agile maneuvering and navigation in unstructured environments poses many challenges for mobile robots. The ability to quickly effect changes in heading and orientation at high speeds in uneven terrain in a manner that is robust to unexpected disturbances is needed for large-obstacle avoidance and responsiveness to navigational commands. The Sprawl family of robots we have developed [1] have demonstrated the ability to locomote forward over unstructured terrain in a fast (over 5 body-lengths per second) and robust (over hip-height obstacles) manner (see Figs. 1 & 2). Taking inspiration from the cockroach *Blaberus discoidalis*, the Sprawl robots employ passive properties and a simple open-loop motor activation pattern to create straight-ahead running and reject disturbances without sensory feedback. In this paper, we extend their behavior to dynamic maneuvering by first exploring turning strategies for dynamic hexapedal systems, then characterizing the behavior using system identification techniques.

Most previous six-legged robots have relied on statically-stable walking strategies, where turns are achieved by specifying either the kinematic trajectory or the force produced by each leg such that the body turns as desired [2]. Although this affords high

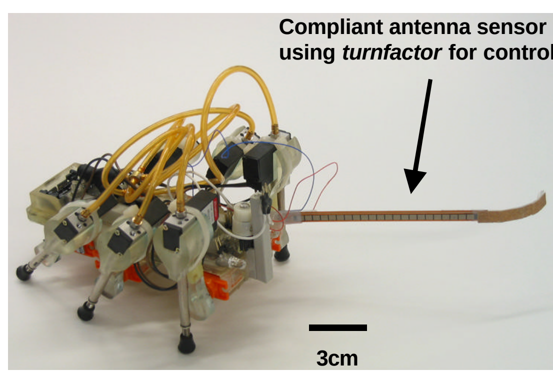

Figure 1. THE SPRAWLETTE RUNNING HEXAPOD. THE SPRAWL FAMILY OF ROBOTS ARE CAPABLE OF FAST AND ROBUST LOCOMOTION WITHOUT SENSORY FEEDBACK. WE NOW EXTEND THEIR BEHAVIOR TO RAPID MANEUVERING FOR NAVIGATION AND WALL FOLLOWING VIA THE PROTOTYPE FLEXIBLE ANTENNA SHOWN HERE.

control over the movement during turning, the speed is limited by the statically-stable assumption. Dynamic hopping machines such as the Raibert monopod [3] are capable of changes in heading through careful foot placement, but lack control over robot orientation in the horizontal plane. Dynamic hexapedal runners such as RHex [4] with rotating legs have employed strategies for turning that slightly alter the rotational leg timing, creating perturbations to forward running [5]. RHex also turns in place by reversing the rotation direction of one side of legs, much like a tank with thread wheels. However, this technique effectively requires the robot to stop before turning. A strategy employed by a similar robot to RHex with rotating legs, Whegs [6], steers the robot by changing the direction of rotation of the front legs, much like an automobile's steering mechanism. For maximum versatility, we would like a strategy that allows us to turn while running forward and to specify the robot trajectory's radius of curvature, including turning in place.

Looking once again to biology, and in particular the cockroach, for inspiration, we see that rapid turns are achieved with minimal changes in the motion of the legs. For example, the cockroach *Periplaneta americana* can not only achieve speeds of over 50 body-lengths per second, but can also rotate by 90° over the course of one stride period [7] and can alternate turns at frequencies of 25 Hz [8]. In the following section, we review studies of dynamic turning in the cockroach that suggest possible strategies for effective turning.

In this paper, we also explore the reduction of the robot's control parameters from 18 to 1. A one-parameter control input for turning, akin to a set of reigns, that coordinates the robot's many degrees of freedom for effective turning would greatly simplify controller design. This parameter reduction can then be used with system identification techniques to characterize the dynamic behavior and limits of the robot. In later sections of this paper, we present experiments and simulations performed to develop such a one-parameter input. This parameter is then used by system identification methods to derive an estimated transfer function between the control input and the rate of change of the robot's heading and orientation. Finally, we present our conclusions and future work.

DYNAMIC TURNING IN BIOLOGY

A many-legged sprawled posture can significantly increase the static stability of a legged platform, but it does not preclude the ability to maneuver dynamically. Studies of the cockroach *Blaberus discoidalis*, the original inspiration for the design and control of the Sprawl robots, indicate that a simple spring-loaded inverted pendulum model can be used to characterize its locomotion dynamics [9]. Given this similarity in locomotion between animals of different morphology and number of legs, it is hypothesized that an advantage of a many-legged sprawled posture lies in increased maneuverability in the horizontal plane.

A closer study of the cockroach's turning dynamics reveals that their remarkable maneuverability can be achieved through minor adjustments in the forces produced by the legs during straight-ahead running, simplifying the requirements for control [10]. It was found that during turning, the frequency of locomotion, the duty cycle of the legs (percentage of the stride period that each leg is in contact with the ground) and the phase differences between the legs are not noticeably different than in straight-ahead running. Moreover, it was found that foot placement (the location relative to the body that the feet contact the ground) and leg sweep angle were not dramatically different during turning. Thus, the cockroach apparently uses the same alternating tripod as in straight-ahead running, relying on the sprawled posture and the mechanics of its locomotion to create rapid changes in heading and orientation.

In particular, it was found that the forces and moments needed for turning originate in asymmetrical changes in leg placement and in the forces generated by the front, middle and hind legs on opposite sides of the body. These changes were observed to be different for each leg. For example, in the front leg on the outside of the turn, the force generated is redirected such that it more perpendicular to the fore-aft axis in the direction of the turn, without a significant change in magnitude. In the middle and hind legs on the outside of the turn, the component of the forces generated that are parallel to fore-aft axis are increased. The legs on the inside of the turn all have either differing touch-down or lift-off positions compared to normal running. The front and rear touch down at different points compared to normal running, while the front and middle lift-off at different points. The inside legs also move through different sweep angles during stance, as the legs are closer to the body at lift-off. Combined, these changes are such that the resulting torques bring forth a coordinated change in heading and orientation.

These studies suggest that turning in hexapedal systems can be achieved with simple changes in the nominal force production and leg placement used for straight-ahead running, while maintaining the same alternating tripod gait. In the following section, we review the design of our robots, and explore whether similar strategies for turning can be achieved.

DYNAMIC TURNING IN SPRAWL ROBOTS

Like the cockroach that inspired them, the Sprawl robots rely on passive mechanical properties to achieve fast and robust locomotion. This locomotion is the result of a form of dynamic balance, in which excitation of the mechanical system by the cyclic open-loop motor pattern results in straight-ahead translation of the center of mass that is stable and robust to perturbations [1]. As the studies of the cockroach suggest, only simple changes to the open-loop configuration may be needed to achieve rapid turns. Initial experiments showed that even small asymmetric changes in the robot's leg configuration or timing of actuation can result in simultaneous changes in heading and orientation. However, given the systems many configuration parameters, it becomes desirable to find optimal ways of coordinating these parameters in order to simplify control. Essentially, we want to collapse the space of configuration parameters to a limited number of independent variables that can then be used for controller design. In this section, we first review the robots' design and survey the available parameters that effect turning. We then describe experiments to determine simple yet effective methods of coordinating these parameters.

Robot Design and Turning Parameters

The basic design of the robots is shown in Figure 2 and consists of a body and legs built up in layers by a process called Shape Deposition Manufacturing [11]. Each leg has two degrees of freedom. The first is in the thrust direction and is accomplished by pneumatic actuators embedded in the leg. The second degree of freedom is passive and consists of a visco-elastic element that allows rotation mostly in the sagittal plane. This leg design is inspired by the trochanter-femur joint in cockroaches, which is believed to be mostly passive in the sagittal plane. Each leg is attached to one of six servo motors embedded in the body of the robot. Movement of the servo motors orients the equilibrium position of the compliant hip joints in increments of 0.8 degrees in the sagittal plane. For straight-ahead running, the legs are arranged in a sprawled posture, as shown in Figure 2. This arrangement is also based on studies of the cockroach, which show that front, middle and hind legs perform very different functions in term of acceleration and deceleration [1]. Each leg is controlled by a small solenoid valve, which regulates air to the piston from a high-pressure source, causing the leg to extend or retract. Locomotion is achieved by alternately activating the valves of each tripod of legs according to a simple binary motor pattern. This motor pattern dictates the frequency and duty cycle with which the valves are activated. Thus, the parameters of the open-loop configuration of the system are the leg angles (LA), as determined by the position of the servo motors, the relative phase and duration (or duty cycle, DC) of activation of the valves. Since all these parameters can be altered independently for each leg, there are 18 configuration parameters in total.

Turning Experiments - Initial Reduction of Parameters

The following experiments were performed on the Sprawlette robot and also in the MSC ADAMS simulation package. The model created in ADAMS [12] has a rigid body with six legs. Each leg is modeled as a prismatic actuator attach to the body by a compliant revolute joint. The floor contact model allows drag and bounce to occur between the ground and the feet and/or four body corners. Initial experiments were performed to determine the configuration parameters that have the greatest effect on turning. The experiments consisted of measuring turning

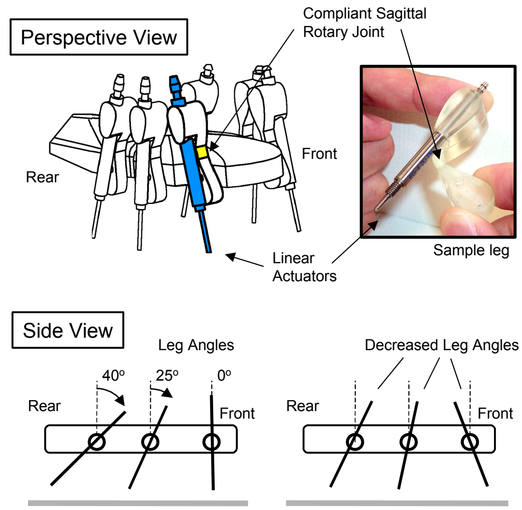

Figure 2. BASIC DESIGN OF THE SPRAWLETTE ROBOTS. TURNING CAN BE ACHIEVED BY CHANGES IN THE ACTIVATION SIGNAL SENT TO THE PISTONS, AND BY CHANGES TO THE LEG ANGLES.

performance as the parameters were varied from a base set of values. These values were the configuration parameters found to be optimal for forward running based on direct experimentation. For simplicity, we first limited the parameter set to 12 by imposing a strict alternating tripod gait in which there is no phase difference in activation between the legs that make up each tripod. Thus, the remaining parameters were the angles and the duty cycles of each leg.

Permutations on changes in leg angle and duty cycle were investigated for individual legs and for coordinated changes between pairs of legs. Legs were paired contralaterally (opposite sides), ipsilaterally (same side), and by diagonal pairs (see Fig. 3). Combinations of coordinated leg angle and duty cycle changes were also considered. These tests revealed that ipsilateral leg angle changes had the highest impact on turning performance out of all the parameters. More specifically, the tests showed that changes to the inside front and rear leg angles were most significant. Using intuition gained from these tests, coordinated changes in parameters between 3 and 4 legs were studied. As seen previously, ipsilateral leg angle changes continued to show the highest impact on turning. More surprisingly, the simultaneous application of duty cycle and leg angle changes did not result in significantly better turning over using leg angles alone. Thus, it became clear that a simple, yet effective, strategy for turning was to utilize only ipsilateral leg angle changes, thereby reducing the parameter space to 3 degrees of freedom.

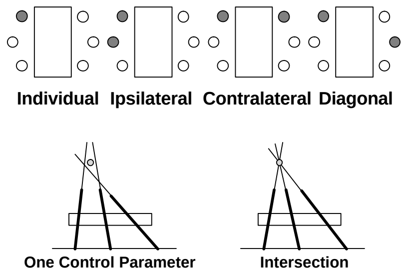

Figure 3. TOP ROW: INDIVIDUAL LEGS AND PAIR COMBINATIONS (IPSILATERAL, CONTRALATERAL, DIAGONAL) WERE THE BASIC GROUPS TESTED IN THE PARAMETER REDUCTION INVESTIGATION. BOTTOM ROW: LEG ANGLES CAN BE CHANGED EITHER INDEPENDENTLY, OR BY CONSTRAINING THEM TO INTERSECT AT A SINGLE POINT.

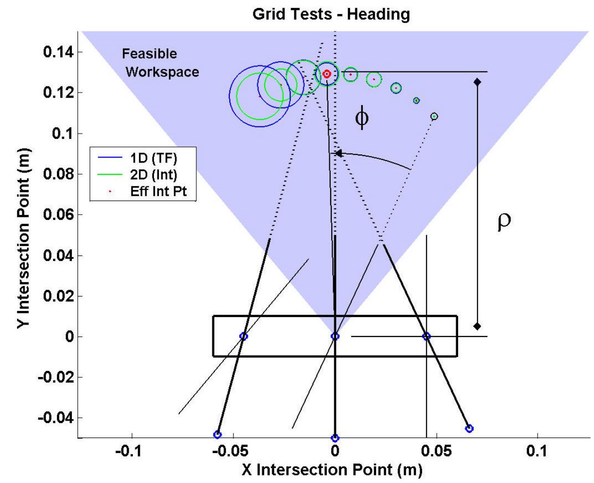

Figure 4. CONSTRAINING THE LEGS SUCH THAT THEIR DIRECTIONS INTERSECT AT ONE POINT IN THE SAGITTAL PLANE PROVIDES AN INTUITIVE WAY OF COORDINATING THE THREE LEGS DEGREES OF FREEDOM. HERE, THE POSITION OF THE INTERSECTION POINT IS GIVEN IN POLAR COORDINATES (ρ AND ϕ) FROM THE LOCATION OF THE MIDDLE LEG'S HIP, WHERE ϕ IS RELATIVE TO THE NOMINAL MEAN LEG ANGLE. IN THIS FIGURE, $\phi=25^o$ AND ρ=0.124m. THE SHADED REGION REPRESENTS THE RANGE OF FEASIBLE INTERSECTION POINTS. OUTSIDE THIS REGION, PERFORMANCE DECREASES MARKEDLY. THE FRONT OF THE ROBOT IS FACING THE RIGHT SIDE OF THE FIGURE

Turning Experiments - Coordinating leg angle changes

Two strategies were investigated for coordinating changes to the ipsilateral leg angles. In the first, the leg angles for all three legs on the inside of the turn are altered by the same amount. Here, there is only one control variable, the amount of leg angle change. While this strategy provides a simple single control parameter to effect turning in the robot, it was felt that a two parameter strategy might provide more options for turning while affording more intuition about the other impacts of changing the leg angles on the locomotion.

Thus, the second strategy considered was one in which the parameter space is reduced to two. An intuitive way of reducing the three leg angles to two parameters was to constrain the leg angles such the lines along each of the legs intersect at one point while the robot is suspended in air. This intersection point can be placed anywhere in the sagittal plane of the robot and its planar coordinates become the two control parameters (see Fig. 4). In this case, we define the intersection point in polar coordinates, with the origin set at the hip of the middle leg. Here ρ is the radial distance of the intersection point from the middle hip joint, and ϕ is the angle of the between the current and nominal intersection points.

The notion of an intersection point is inspired by studies of stability in walking, which utilize concepts such the Zero Moment Point (ZMP) and Center of Pressure (COP) [13] [14]. In this case, the use of the intersection point allows us to approximately decouple the effects of the leg angle changes on stability and whole-body force production. The smaller the value of ρ, the more sprawled the leg angles become. The sprawl of the legs has been observed to directly affect the stability of locomotion, with higher sprawl angles resulting in more stable locomotion. The value of ϕ determines the general direction of force production of the three legs. Altering this direction on both sides of the robot can cause changes in forward speed and even locomotion direction, while changing the general leg direction on only one side causes turning. Thus, we introduce this notion of the intersection point not only as a means of reducing the parameter space for turning control, but also as a starting point for future studies on stability and forward speed control.

Turning Experiments - Grid Tests

In these experiments, we examined the effect on turning performance of changing the location of the intersection point of the three legs on the inside of the turn. The location of the intersection point was varied in a grid in the sagittal plane above the body (similar to Fig. 4, but in grid format). The grid space was explored and characterized over a wide range of configurations (close to 500 grid points) that fully covered the achievable parameter space.

The grid based parameter investigation brought some key points to light. The grid trends are clearly radial in nature (see Fig. 5). The center of these radial trends seems to closely match the middle leg hip joint which is also near the center-of-mass of the robot, indicating that this was an appropriate choice for the origin of the coordinate space. It was clear that in all the testing, moving the location of the intersection point further away from

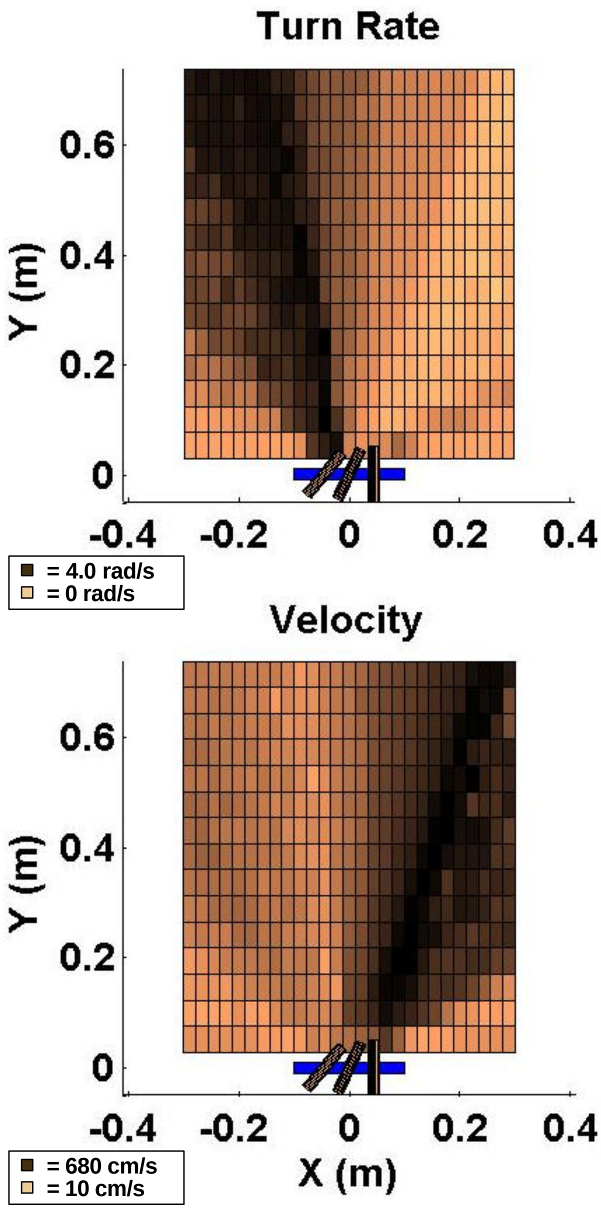

Figure 5. *FIX SPEED SCALE* RESULTS OF VARYING THE LOCATION OF THE INTERSECTION POINT OF THE LEG ANGLES OVER A GRID IN THE SAGITTAL PLANE. THE TESTS SHOW THAT THE TRENDS IN TURNING RATE AND FORWARD VELOCITY ARE RADIAL WITH AN ORIGIN NEAR THE LOCATION OF THE MIDDLE LEG.

the origin had very little effect on turning. The main effect was created by sweeping the intersection point forward or backward or by changing the angle with the vertical. In all of the simulations, 3 metrics of turning performance were measured (change in body yaw or heading, lateral displacement and forward velocity).

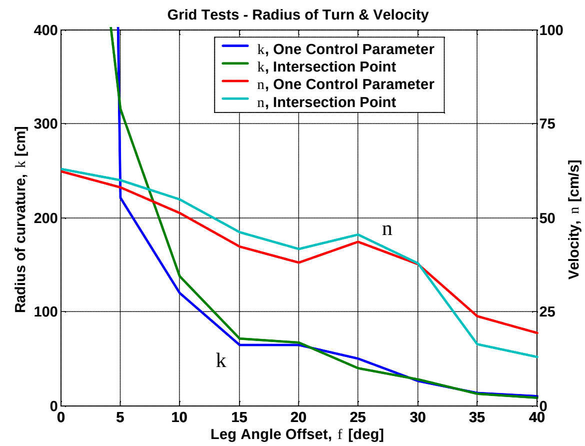

Figure 6. TURNING RADIUS κ, AND VELOCITY ν DECREASE AS TURNING RATE INCREASES.

As expected, the forward velocity decreases as the intersection point moves away from its nominal value (see Fig. 5). Changing the angle of the intersection point has an interesting effect on heading. Changing the angle toward the front in, for example, the right side legs causes the robot to turn slightly left. However, changing this angle toward the back causes a dramatic turn towards the right. Thus, turning is most effectively achieved by moving the intersection point towards the back of the robot. As this point is moved further back, slippage eventually causes both velocity and change in heading to decrease. Over the full range of the grid testing the turn rate varied from zero (at nominal leg angles) to 4.01 rad/s for the best turn. The nominal forward velocity varied from 680 cm/s (at nominal) to around 10 cm/s.

The turning radius, another metric of turning performance, can be defined as the radius of curvature of the trajectory of the robot during a turn. This radius can be computed as the ratio between forward velocity and turning rate. As discussed above, changes to the intersection point that increase the turning rate also decrease forward velocity. As a result, the turning radius is inversely related to ϕ, as shown in Figure 6. Thus, while small turning radii can be achieved, they are accompanied by slow forward velocities. However, the velocity drops gradually so that fairly sharp turns can be obtained at $\frac{1}{3}$ the maximum velocity.

Turning Experiments - Conclusions

Based on these results, we conclude that moving the intersection point of the inside legs along an arcing path from forward to backwards is a simple and effective method of coordinating the parameter space to achieve turning. The grid tests have indicated the changes in ρ do not significantly affect the turning results. Therefore, an appropriately chosen radius can generate a wide range of turns (see Fig. 5). We call the single control parame-

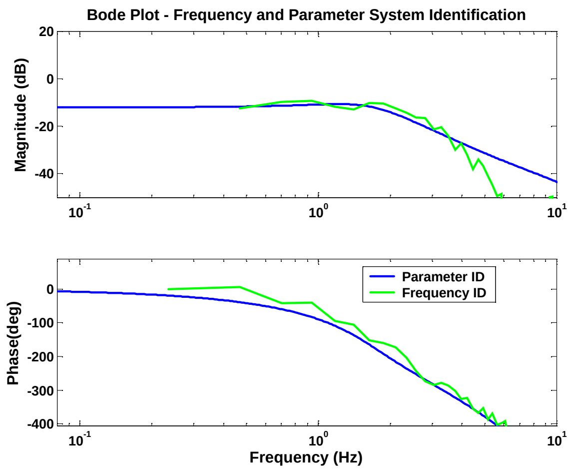

Figure 7. EXPERIMENTAL BODE DIAGRAM OF THE SYSTEM FOUND USING BOTH FREQUENCY DOMAIN AND PARAMETER (ARMAX) IDENTIFICATION TECHNIQUES. BOTH METHODS APPEAR TO BE IN CLOSE AGREEMENT. THE BANDWIDTH OF THE SYSTEM IS NEAR 1HZ, WHICH IS ROUGHLY 7 TIMES THE STRIDE FREQUENCY AND CLOSE TO $\frac{1}{3}$ THE VALUE OF THE BANDWIDTH OF THE SERVO MOTORS THAT CONTROL EACH LEG'S ANGLE.

ter that describes the displacement of the intersection point along this arc the "turnfactor" (TF). The simplicity of the TF is attractive for applications such as system identification for turning dynamics, as shown in the following section, and for higher-level navigation control schemes such as antenna-based wall following [15].

SYSTEM IDENTIFICATION

Given a convenient control parameter for turning, we are now interested in characterizing maneuverability performance, that is, determining the range of maneuvers that can be achieved. System identification techniques [16] can be used to explore the performance space of the system. In the robot, the leg angles are a key robot parameter and are controlled by servo motors. Thus, the dynamics of the servo motors have a direct effect on the ability to control the turn and are thus included in the entire system dynamics. In this section, we present two different system identification techniques to characterize the turning dynamics and compare their results.

Frequency Domain Identification

The first method of analysis used in system identification is Frequency Domain Identification. This method involves comparing system input and output data as a function of frequency, resulting in an experimentally determined Bode diagram. By using an input signal with content at a wide range of frequencies, the magnitude and phase response can be determined over a broad range. For both system and servo, the input was the turn factor parameter described in the previous section. A swept sine wave from 0.1Hz to 10Hz with an amplitude of 20° was used as input for both system and servo. The servo output was the voltage at an internal potentiometer connected to the output shaft. The system output was measured as body heading in degrees. The body heading was determined by tracking the positions of 2 bright beacons placed near the front and rear of the body using a high-speed video camera. After system identification techniques were applied to the swept sine input and output data, the frequency response of the system and servo were both determined (see Fig. 7). The servo motors have been found to have a bandwidth of 2-3Hz, which is where the magnitude and phase begin to fall off. The entire system was found to have a bandwidth around 1Hz. Thus, the over-all system dynamics have a bandwidth that is almost 3 times slower than the servo dynamics.

Parametric System Identification

The second method used for system identification is Parametric Identification. Here, we assume a structure for a parameter-based model of the system, and then determine values of the parameters that cause the model response to most closely match experimental data. The three principal model structures that are used in parametric identification are called ARX, ARMAX and Box-Jenkins. These model structures have the form of transfer functions between the control input and turning rate output. The system model is found by first assuming the order of the transfer function's numerator and denominator, and in some cases also the order of the noise model's numerator and denominator, and then using the methods to find the values of the parameters. The main differences between the ARX, ARMAX and Box-Jenkins models are in the way that the noise is characterized. The frequency identification results previously described suggest that there are 4^{th} order dynamics present due to the servo dynamics. The three model structures, using orders of the numerator and denominator from 2 to 6 were applied to the experimental data previously described. The 5^{th} order ARMAX model was selected as having the best fit to the data. The numerator and denominator of this model of the system are 5^{th} order, and the numerator of the noise model is 4^{th} order. The identified system transfer function (TF_{PID}) is Eqn (1) and its roots are shown below.

$$\frac{(-1.84s^4+4.38s^3-4.48s^2-2.50s+8.85)\times 10^{-3}}{s^5-2.28s^4+1.61s^3+0.198s^2-0.161s+0.0418} \quad (1)$$

Zeros: (-1.02, 0.932±1.48i, 1.54)
Poles: (-0.311, 0.898±0.140i, 0.399±0.0615i)

The frequency response of this transfer function, that is, the Bode diagram, was compared to the experimental frequency response previously described. The two system identification techniques generated Bode plots which show similar results (see Fig. 7). These results show that the system bandwidth is around 1Hz. The similarities between the two system identification approaches suggest that active servoing during dynamic robot locomotion is not feasible at the nominal 7Hz stride frequency. However, adjustments in leg angles (turnfactor) can be made that will effect rapid turns over a few strides. The transfer function from parameter identification is now available for future use in control designs on this robot, and can be used to ease the task of closing a control loop around a maneuverability task.

CONCLUSIONS

The fast and robust forward locomotion of the Sprawl robots can be easily extended to dynamical turning by simple changes in the robot's configuration. This strategy is inspired by studies of dynamic turning in the robot's exemplar, the cockroach. Small changes in configuration create changes in leg force production that result in net forces and moments that alter the heading and orientation of the robot over a stride. These changes in leg force direction are accomplished by changes in the equilibrium angle of the legs' compliant hip joint. It was found that these leg angles can be coordinated by a single "turnfactor" that can serve as a control input for further studies on navigation that require agile maneuvering. In this paper, we have characterized the robot's turning dynamics, including a transfer function between the turn factor and the turning rate of the robot. Current [17] work is focused on versions of the robots with full autonomy. Currently, the robots are tethered to provide power and control. This tether can significantly influence the turning dynamics and limit maneuverability. Ongoing work is also extending the behavior of the Sprawl robot for increased adaptability to changing environments [18] and to navigation via wall-following using an antennae-based sensor [15]. This study of antennae-based navigation will utilize the results of this paper to design appropriate controllers for optimal performance.

ACKNOWLEDGEMENTS

The authors thank the members of the Stanford CDR and Biomimetics Lab and also the Berkeley PolyPEDAL lab for their contributions to the work documented in this paper. This work is supported by the Natl. Science Foundation under grant MIP9617994 and by the Office of Naval Research under N00014-98-1-0669.

REFERENCES

[1] Cham, J. G., Bailey, S. A., Clark, J. E., Full, R. J., and Cutkosky, M. R., October 2002. "Fast and robust: Hexapedal robots via shape deposition manufacturing". In Proceedings of International Journal of Robotics Research, vol. 21.

[2] Waldron, K. J., Vohnout, V. J., Pery, A., and McGhee, R. B., 1984. "Configuration-design of the adaptive suspension vehicle". International Journal of Robotics Research, **3** (2) , pp. 37–48.

[3] Raibert, M. H., 1986. "Legged robots". Communication of the ACM, **29** (6) , pp. 499–514.

[4] Saranli, U., Buehler, M., and Koditschek, D. E., 2001. "Rhex: A simple and highly mobile hexapod robot". International Journal of Robotics Research, **20** (7) , pp. 616–631.

[5] Full, R. J., Kubow, T., Schmitt, J., Holmes, P., and Koditschek, D., 2002. "Quantifying dynamic stability and maneuverability in legged locomotion". Integrative and Comparative Biology, **42** (1) , pp. 149–157.

[6] Bachmann, R. J., Kingsley, D. A., Offi, J., Quinn, R. D., Nelson, G. M., and Ritzmann, R. E., 2001. *Insect designs for improved robot mobility*. Addison-Wesley.

[7] Camhi, J. M., and Levy, A., 1988. "Organization of a complex movement - fixed and variable components of the cockroach escape behavior". Journal of Comparative Physiology A-Sensory Neural and Behavioral Physiology, **163** (3) , pp. 317–328.

[8] Camhi, J. M., and Johnson, E. N., 1999. "High-frequency steering maneuvers mediated by tactile cues: antenna wall-following in the cockroach". *Journal of Experimental Biology,* **202** February , pp. 631–643.

[9] Full, R. J., and Farley, C. T., 2000. "Musculoskeletal dynamics in rhythmic systems - a comparative approach to legged locomotion". *Biomechanics and Neural Control of Posture and Movement* .

[10] Jindrich, D. L., and Full, R. J., 1999. "Many-legged maneuverability: Dynamics of turning in hexapods". *The Journal of Experimental Biology,* **202** , p. 1603 1623.

[11] Cham, J. G., Pruitt, B., Cutkosky, M. R., Binnard, M., Weiss, E., and Neplotnik, G., September 1999. "Layered manufacturing with embedded components: Process planning issues". In ASME Proceedings, DETC '99.

[12] Clark, J. E., Thelen, D. G., and Cutkosky, M. R., 2004. Dynamic simulation and analysis of a hexapod running robot, March. Submitted to ASME International Mechanical Engineering Congress and Exposition.

[13] Dordevic, G., Rasic, M., and Shadmehr, R., 2003. "Parametric models for motion planning and control in biomimetic robotics". *Submitted to IEEE Transactions on Robotics* October . Paper no. W03-017.

[14] Vukobratovic, M., Borovac, B., and Surdilovic, D., 2001. "Zero-moment point-proper interpretation and new applications". *IEEE-RAS International Conference on Humanoid Robots* November .

[15] Cowan, N. J., Ma, E. J., Cutkosky, M. R., and Full, R. J.,

2003. “A biologically inspired passive antenna for steering control of a running robot”. In International Symposium on Robotics Research.
[16] Ljung, L., 1999. *System Identification: Theory for the User*, 2nd ed. Prentice-Hall.
[17] Kim, S. B., Clark, J. E., and Cutkosky, M. R., March 2004. Independent sprawl robot. Tech. rep., Stanford University, Stanford, CA 94305.
[18] Cham, J. G., Karpick, J., and Cutkosky, M. R., 2004. “Stride period adaptation for a biomimetic running hexapod”. International Journal of Robotics Research, **23** (2) , pp. 141 – 153.