A Biologically Inspired Passive Antenna for Steering Control of a Running Robot

Noah J. Cowan[1], Emily J. Ma[2], Mark Cutkosky[2], and Robert J. Full[3]

[1] Dept. of Mech. Eng., Johns Hopkins University, Baltimore, MD 21218, USA
[2] Dept. of Mech. Eng., Stanford University, Palo Alto, CA, 94305, USA
[3] Dept. of Integrative Bio., University of California, Berkeley, CA, 94720, USA

Abstract. Inspired by nature's effective use of tactile feedback for rapid maneuvering, we designed a passive, highly compliant tactile sensor for Sprawlette, a hexapedal running robot. To bridge the gap between biology and design, we took initial steps toward understanding how the cockroach, *Periplaneta americana*, uses antenna feedback to control its orientation during a rapid wall following behavior. First, we developed a simple *template model* for antenna-based wall following. Second, we collected initial cockroach data that supports the idea that the rate of convergence to the wall or "tactile flow" is being used, in part, for controlling body orientation. Based on these steps, we designed and calibrated a prototype tactile sensor to measure Sprawlette's angle and distance relative to a straight wall, and employed a simple bio-inspired control law that can stabilize the template dynamics. Finally, we integrated the sensor and controller on Sprawlette and showed empirically that stabilizing Sprawlette during wall following does indeed require tactile flow, as predicted.

1 Introduction

Animals execute split-second maneuvers to avoid obstacles, catch prey and evade predators amidst a myriad of information from thousands of sensors such as vision and touch. This paper tackles the challenge of closing sensory feedback loops in robotics by deriving inspiration from one of nature's most adept locomotors, the cockroach *Periplaneta americana*. In particular, we present a new passive tactile sensor, similar in structure and function to a cockroach antenna, and describe its application to the control of rapid maneuvering of a hexapedal robot, Sprawlette [6].

For mobile robots, tactile sensing provides a compelling alternative to traditional sensing methods, such as sonar, capacitive or inductive proximity sensors, that are highly dependent on the sensed object's surface roughness, reflectivity and material properties. Vision-based methods, though very flexible, are computationally expensive and can fail under low light conditions or high air-particle content.

Often active in low light levels, insects commonly rely on non-visual senses for self-orientation and navigation. Specialized mechanoreceptors for detecting contact and strain on filamentous support structures such as animal vibrissae or arthropod antennae (see Fig. 1) provide tactile cues from the physical

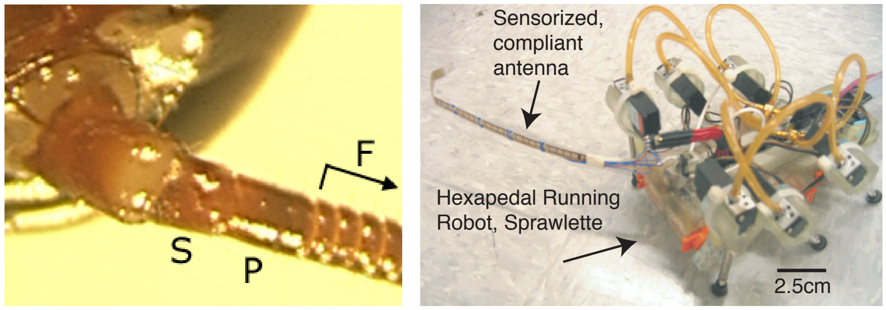

Fig. 1. *Left.* The antennae of the cockroach *Periplaneta americana* is actuated by its first two proximal segments, called the Scape (S) and Pedicel (P). The Flagellum (F) possesses 150-170 passive segments. *Right.* Sprawlette, a hexapedal robot, is shown with our prototype artificial antenna.

environment to augment poor or non-existent visual guidance. When moving slowly, cockroaches actively probe their surroundings by sweeping their antennae through the environment [12]. During rapid locomotion, however, the base is held more-or-less fixed, while the long, passive (unactuated) flagellum bends in response to objects in its environment [4]. Specialized mechanoreceptors measure contact and strain, which the cockroach uses to control rapid maneuvers, achieving up to 25 turns/second in response to environmental stimuli [4].

Touch probes for mobile robots often take the form of active, actuated cantilever beams that are swept back and forth through the environment. When the free end of such a beam is loaded due to contact with an external object a bending moment is sensed at the base [10,13,18]. Passive sensing has also been effective [2,14,17], although these methods require slowly moving platforms to serve the sensor. Recently, Barnes et al. [1] have built and analyzed a large-deflection, passive biomimetic lobster antenna containing three binary bending sensors that can distinguish obstacles from water flow. Other tactile sensors for mobile robots include proximity sensors used for obstacle avoidance [3,8,11]. Additionally, whisker sensor arrays have been used to control ground contact in legged locomotion [15].

Sprawlette (see Fig.1) runs several body lengths-per-second, rendering slow, active tactile feedback methodologies infeasible. Thus, we seek a highly compliant, robust and passive sensor that provides just enough information for stable, rapid maneuvering.

2 Horizontal-Plane Template Dynamics

Animal and machine locomotion results from complex, high-dimensional nonlinear, dynamically coupled interactions between an organism or mechanism

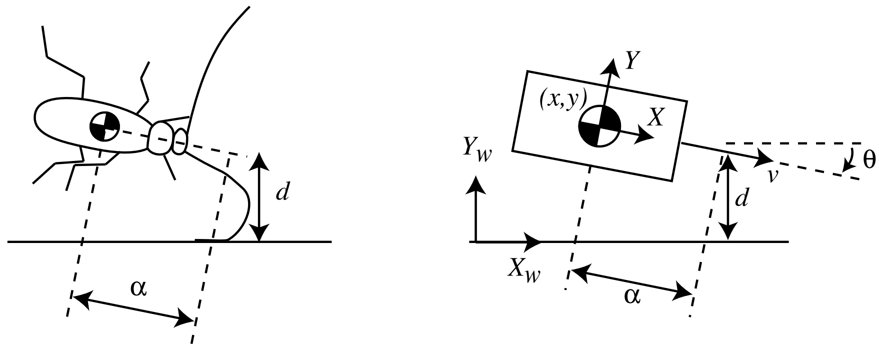

Fig. 2. *Left:* Schematic of a cockroach running along a wall. The antenna contacts the wall a distance α along the cockroach centerline. From that point, the wall is a distance d from the cockroach centerline. *Right:* Schematic of the template model; α is assumed constant. Counterclockwise rotations are positive, thus the body orientation, θ, is negative as shown.

and its environment. Nevertheless, Full and Koditschek hypothesize the dynamics of locomotion may often be captured by a simple, low-dimensional model, called a *template* [7]. As they describe, a single template model often describes the mechanics of a behavior across a wide variety of animals and machines, with varying skeletal type, leg number, posture and size.

We present a simple template model that takes a first step toward explaining antenna-based maneuvering. We build on the template idea by incorporating sensor mechanics directly in the model. The model serves two purposes. First, it enables us to generate simple, refutable hypotheses about biological neuro-control. Second, it helps us map out the design space for our bio-inspired artificial antenna and controller, enabling us to implement a successful wall following behavior with Sprawlette.

Prior work has considered hybrid template models that operate from "stride-to-stride," such as the Spring Loaded Inverted Pendulum (SLIP) [5] or Lateral Leg Spring (LLS) [16]. We further simplify the turning dynamics by considering a continuous model that neglects the details of individual foot-fall patterns, in an effort to understand the multi-stride phenomena of wall following. Although cockroaches can move sideways, Jindrich and Full [9] showed that rapid turns are often generated by a set of forces and moments that keep the heading – the velocity of the center of mass (COM) – in line with the body orientation. Similarly, despite external perturbations, Sprawlette also robustly maintains forward running. Thus, we approximate the dynamics with a second order system incapable of "side-slip."

Consider a planar body with 3 degrees of freedom (DOF), and attach a reference frame to the COM, with the X-axis pointing toward the front of the body as shown in Fig. 2. Suppose there is a straight wall in the workspace and attach a world frame as shown. Denote the body orientation θ and position

(x, y), relative to (X_w, Y_w). Let ω denote the rotational velocity of the body. Assuming no side-slip, the body velocity vector can be expressed with respect to the body-fixed reference frame as $V = [v, 0]^T$, where v is the forward speed of the body. Thus, we have

$$\dot{\theta} = \omega, \quad \dot{x} = v\cos\theta, \quad \dot{y} = v\sin\theta\,.$$

Roughly speaking, Camhi and Johnson [4] hypothesize that while running along a wall, a cockroach uses antenna strain and/or contact information to estimate its "head-to-wall" distance. Specifically, we assume that the antenna measures ahead of the COM a distance α, and measures the distance from the body centerline to the wall, d. Under these assumptions, we have

$$d = \alpha\sin\theta + y \implies \dot{d} = \omega\,\alpha\cos\theta + v\sin\theta\,. \tag{1}$$

We assume that a net moment u acts as a control input to the template model. The polar moment of inertia m and damping coefficient[1] b parameterize the dynamics, i.e. $m\ddot{\theta} + b\dot{\theta} = u$. The forward speed, v, is considered fixed. From (1), for small θ, $\dot{d} \approx \alpha\dot{\theta} + v\theta$. Combining, we obtain

$$G(s) = \frac{D(s)}{U(s)} = \overbrace{\frac{\alpha s + v}{s}}^{\text{sensing}} \cdot \overbrace{\frac{1}{ms^2 + bs}}^{\text{mechanics}}\,, \tag{2}$$

where U and D are the Laplace transforms of u and d, respectively, and G is the resulting transfer function.

The system above has eight parameters, including the dimensionless angle, θ, and six dimensional quantities: complex frequency, s; head-to-wall distance, d; input moment, u; polar moment of inertia, m; damping, b; look-ahead distance, α; and forward velocity, v. Defining dimensionless complex frequency $\widetilde{s}$, these reduce to four dimensionless groups: $\widetilde{u} = u\frac{\alpha^2}{mv^2}$, $\tau = \frac{mv}{b\alpha}$, $\widetilde{d} = d\frac{1}{\tau\alpha}$, θ; with $\widetilde{s} = s\frac{\alpha}{v}$. From (2) the dimensionless transfer function relating $\widetilde{u}$ and $\widetilde{d}$ can be written $\widetilde{G}(\widetilde{s}) = \frac{(\widetilde{s}+1)}{\widetilde{s}^2(\tau\widetilde{s}+1)}$.

The dimensionless parameter τ describes the behavior of the open-loop transfer function. If the cockroach uses negative feedback from the antenna-based distance measurement d, then τ puts constraints on what control structures can stabilize the system. The simplest possible feedback strategy might be proportional feedback (P-control) of the form $u = -K_P(d - d^*)$. An important question is whether such a naive strategy can stabilize the model. Under proportional feedback the closed-loop dynamics are given by $G_{\text{CL}} = K_P G/(1 + K_P G)$. Root locus analysis on the gain K_P leads to three qualitatively distinct cases:

1. $\tau > 1$. The system cannot be stabilized with P-control.

[1] Damping is used to model stride-to-stride frictional and impact losses.

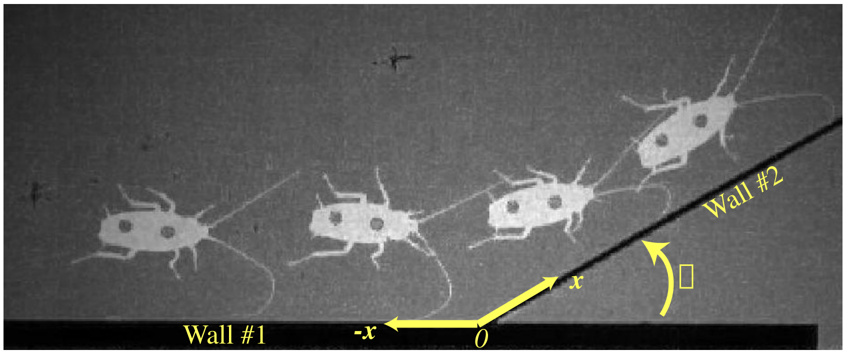

Fig. 3. Multiple exposures of a cockroach running along wall #1 until it reaches an angle change and then begins running along wall #2. The distance traveled along the wall is x, and $x = 0$ corresponds to where wall #2 intersects wall #1. The angle of wall #1 relative to wall #1 is given by ϕ.

2. $\tau_{\text{crit}} < \tau \leq 1$, where $\tau_{\text{crit}} \approx 0.1$. For all choices of the gain K_P, the system will be under damped and oscillatory.
3. $\tau \leq \tau_{\text{crit}}$. The system can be stabilized with P-control, and for an appropriate choice of K_P, the system can be under, over or critically damped.

3 Biological Hypothesis: Feedback from Tactile Flow

Accurately characterizing the parameters for a cockroach represents work in progress. Estimating bounds for b is challenging as it requires estimating energy dissipation during turns, which may not be feasible. Nevertheless, the system can easily be stabilized for all τ with proportional-derivative feedback (PD-control) of the form $u = -K_P(d - d^*) - K_D\dot{d}$, where (K_P, K_D) are the feedback gains. It may also be possible to feedback the angle, in addition to distance, $u = -K_P(d - d^*) - K_\theta\theta$, with gains (K_P, K_θ), respectively. Note that, intuitively, $\dot{d}$ and θ are closely related, and give a measure of the rate of convergence to the wall. However, one can achieve infinite gain margin with PD-control, but not necessarily with Pθ-control. In addition to the PD and Pθ hypotheses, there are many other alternatives, such as nonlinear feedback.

Although we do not have an accurate estimate of τ for a cockroach, the above model suggests that simple proportional error feedback may be insufficient. Motivated by this observation, we made preliminary tests of the hypothesis that P-control, based on the cockroach-to-wall distance d, is not enough, and that the cockroach neuro-controller for wall following also has a rate or angle component. We refer to the rate $\dot{d}$ as *tactile-flow*.

As a preliminary test of the tactile flow hypothesis, we recorded two cockroaches at 500Hz as they encountered a change in wall angle, as depicted in Fig. 3, and digitized the video to extract positions and orientations. The trials consisted of 12 runs with a $\phi = 30^o$ change in wall angle and 6 with a

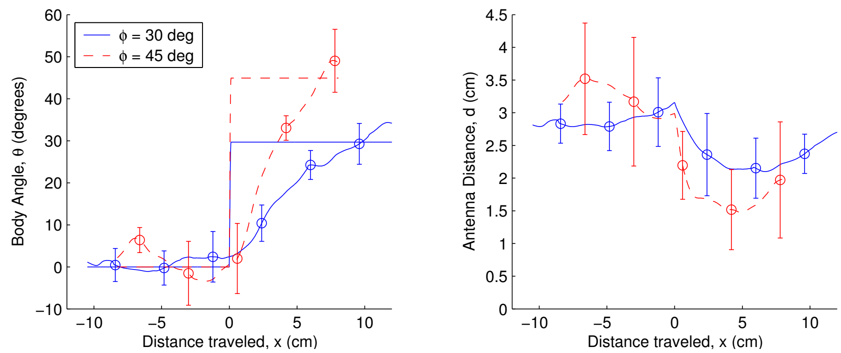

Fig. 4. Preliminary data of cockroaches encountering a wall angle change with their antenna. The error bars represent 95% confidence intervals for the mean of the data.

$\phi = 45^o$ change. In very few of the trials did the cockroach body hit the wall. Since each animal ran at a slightly different speed in each trial we normalized the data relative to the distance traveled along the wall, i.e. the x component of the position. The point $x = 0$ corresponds to the instant when the base of the antenna becomes closer to wall #2 than wall #1 (see Fig. 3). For $x < 0$ we measure x along the first part of the wall, and for $x > 0$, we measure x along the ramp.

As seen in Fig. 4, the distance traveled before the cockroach is parallel with the ramp is *shorter* for the *larger* angle, ϕ. We believe that this is a result of tactile-flow feedback or, possibly, that the antenna can measure the angle relative to the wall (as we do for our artificial sensor in Sect. 4). Therefore, preliminary data suggest that distance feedback alone is insufficient to explain this behavior.

4 Biological Inspiration: A Compliant Antenna

For our prototype artificial antenna, we employed a slightly modified, highly compliant and lightweight flex sensor from Spectra Symbol[2] that changes electrical resistance in proportion to strain, for very large deflections.

The dynamical analysis from Sect. 2, and the biological observations from Sect. 3, suggest that an estimate of distance d and angle θ of Sprawlette relative to a contact surface is desirable. Assuming that the local curvature (and thus local resistance) along the sensor is some function of distance and angle, we used a simple least-squares approach to calibrate the antenna to measure distance and angle.

As shown in Fig. 5, the antenna emanates from the base at 45° relative to the body. We electrically divided the sensor into $n = 5$ segments, and

[2] `http://www.spectrasymbol.com/bend.html`

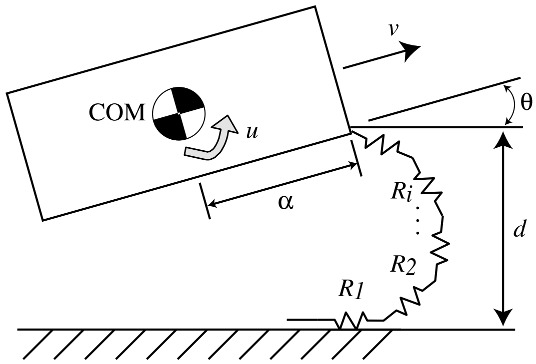

Fig. 5. The artificial antenna is divided into several resistance segments, R_i, $i = 1 \dots N$, enabling measurement of curvature, at several points along the antenna. From the resistances, we estimate the distance d and angle θ.

measured the resistance, a correlate of local strain, at each point along its length, $R_1, R_2, \dots, R_n$. Then, we fit the following affine model:

$$y = Ax, \quad \text{where} \quad y = \left[d, \theta\right]^T, \quad x = [R_1, R_2, \dots, R_n, 1]^T, \tag{3}$$

and $A \in \mathbb{R}^{2\times(n+1)}$ are the model parameters. To calibrate the antenna, we placed Sprawlette in several positions and orientations relative to a surface, and measured the resulting resistance values on the n segments. Each trial resulted in a pair $\left(x^{(i)}, y^{(i)}\right)$, $i = 1, \dots, N$. We collected trials for 11 angles ranging from $-20°$ to $30°$ and 7 wall distances ranging from 60 to 120 mm.

The results of a least-squares fit are shown in Fig. 6. The resulting mean-squared errors are 4.5 mm (7.5%) and 7.2° (15%). It appears that a nonlinear model would provide a better fit for angle. As a simple test, we restricted the data to a distance range of 60 to 80 mm, which reduced the angular mean-squared error to 4.9° (10%).

5 Antenna-based Wall Following for Sprawlette

Sprawlette is a highly compliant robot with six legs, and two actuators per leg: a low-power *shape actuator* that changes the orientation of that leg's pneumatic *power actuator*. For straight-ahead running, Sprawlette can operate "open loop", by fixing the pneumatic valve timings to generate an alternating tripod gait, and holding the six shape variables to a constant posture [6]. Although cockroaches turn by generating active lateral forces, Sprawlette's kinematics prevent this. Sprawlette can, however, through small changes in shape and duty cycle generate relatively large turning moments. Such changes generate a net angular moment that acts to rotate the body in the horizontal plane. Fortunately, the resulting misalignment of the COM

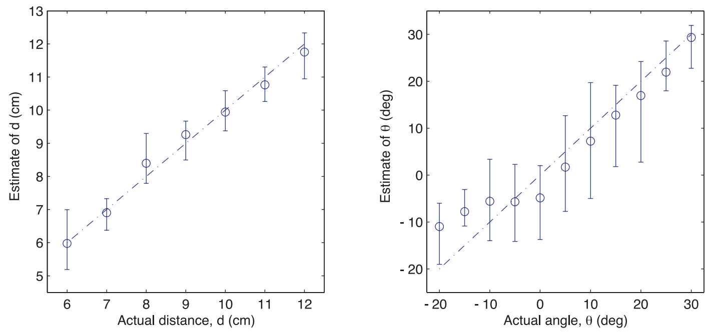

Fig. 6. Least-squares errors for estimates of distance d and angle θ, shown in Fig. 5, using the artificial antenna. Error bars represent the min and max error at each actual distance or angle.

velocity and the body orientation self-corrects via *passive* horizontal forces [6], and thus the template model described in this paper seems plausible.

For our control input, we change the "shape" of Sprawlette as a function of a single parameter, γ. This results in a graded turning moment. Presently, we neglect the dynamics of the servomotors, pneumatic pistons and valves and leg compliance the characterization of which represents work in progress. Therefore, we assume that for sufficiently small shape changes, we have $u = K\gamma$ for some (unknown) gain K, and θ and d evolve as in Sect. 2.

We implemented an analog PD-controller based only on total resistance (i.e. $n = 1$ in Sect. 4). A half-bridge sets the point of nominal distance from the wall. Potentiometers tune K_P, K_D and the nominal head-to-wall distance. Since K is unknown, the effective scales of K_P and K_D are unknown as well. We recorded Sprawlette on a treadmill along a wall, as shown in Figure 7, at several different choices of K_P and K_D, and digitized the video to compute d and θ at each video frame. Table 1 summarizes the experiments. As expected, we are unable to stabilize the robot without adding damping. With carefully hand-tuned gains, the robot reaches a desired distance from the wall within 1 to 2 seconds.

Batch#	N	K_P	K_D	Rise Time	% Overshoot	15% Settling Time
1	3	6.0	0.0	2.0 ± 1.0	1.2 ± 0.1	did not converge
2	2	6.0	0.8	2.7 ± 0.1	2.6 ± 0.8	did not converge
3	5	10.5	1.4	0.7 ± 0.1	$30\% \pm 10\%$	1.9 ± 1.1
4	3	13.2	1.8	1.0 ± 0.6	$28\% \pm 34\%$	1.2 ± 0.4
5	2	17.5	0.0	unstable	unstable	unstable
6	3	17.5	1.4	unstable	unstable	unstable

Table 1. Results for different choices of the feedback gains K_P and K_D.

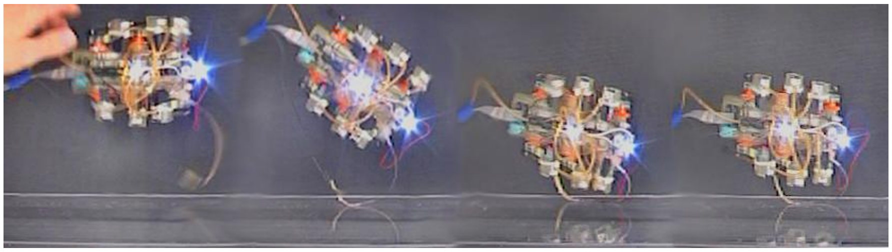

Fig. 7. Multiple exposures of Sprawlette on a treadmill. Initially, Sprawlette was held a few centimeters away from a Plexiglas wall. When released, the robot turns according to a simple PD controller. When the controller is properly tuned, the robot converges to the desired antenna length within 1 or 2 seconds.

6 Conclusions and Future Work

Our mathematical model of antenna-based maneuvering in cockroaches lead to a novel and effective robotic sensor. As our simple model illustrates, tactile flow may represent a critical ingredient for high-speed wall-following and similar maneuvers. Initially, our implementation was based on analog differentiation of the electrical signal corresponding to distance. However, there are many alternatives to explore. For example, feeding back angle, rather than tactile flow, may also lead to high-performance, stable controllers.

Future work will focus on antenna feedback for high-performance locomotion, both in biology and robotics. In addition to "reverse engineering" the cockroach control structure, we wish to explore the mechanics of the antenna, to understand advantages and disadvantages of changing antenna size, shape and stiffness; this will require a comparative study among animals. Understanding these principles will lead us to better future antenna designs.

Acknowledgments

Special thanks to Jorge Cham, Arthur McClung, Jusuk Lee and Tom Libby, and the Stanford Biomimetic Robotics and Berkeley PolyPEDAL laboratories. This work was supported by the Stanford Mechanical Engineering Summer Undergraduate Research Institute, by the NSF under grant MIP9617994, by the ONR under grant N00014-98-10669 and by DARPA/ONR under grant N00014-98-1-0747.

References

1. T.G. Barnes, T.Q. Truong, G.G. Adams, and N.E. McGruer. Large deflection analysis of a biomimetic lobster robot antenna due to contact and flow. *Transactions of the ASME*, 68:948–951, 2001.
2. D. L. Brock and S. Chiu. Environment perception of an articulated robot hand using contact sensors. In *Intl. Conf. on Robotics and Automation*, pages 89–96. IEEE, 1987.

3. R. A. Brooks. A robot that walks; emergent behaviors from a carefully evolved network. In *Neural Computation*, volume 1, pages 253–262. 1989.
4. J. M. Camhi and E. N. Johnson. High-frequency steering maneuvers mediated by tactile cues: antenna wall-following in the cockroach. *Journal of Experimental Biology*, 202:631–643, 1999.
5. G. A. Cavagna, N. C. Heglund, and C. R. Taylor. Walking, running, and galloping: Mechanical similarities between different animals. In T. J. Pedley, editor, *Scale Effects in Animal Locomotion, Proceedings of an International Symposium*, pages 111–125. Academic Press, New York, USA, 1975.
6. J. G. Cham, S. A. Bailey, and J. E. Clark. Fast and robust: Hexapedal robots via shape deposition manufacturing. *The International Journal of Robotics Research*, 21(10), 2002.
7. R. J. Full and D. E. Koditschek. Templates and anchors: neuromechanical hypotheses of legged locomotion on land. *Journal of Experimental Biology*, 202:3325–3332, 1999.
8. S. Hirose, T. Masui, H. Kikuchi, Y. Fukuda, and Y. Umetani. Titan iii: A quadruped walking vehicle. In *Second Int. Symp. on Robotics Research*. MIT Press, Cambridge Massachusetts, 1985.
9. Devin L. Jindrich and Robert J. Full. Many-legged maneuverability: Dynamics of turning in hexapods. *Journal of Experimental Biology*, 202:1603–1623, 1999.
10. M. Kaneko, N. Ueno, and T. Tsuji. Active antenna (basic considerations of a working principle). In *Intl. Conf. on Intelligent Robots and Systems*, volume 3, pages 1744–50. IEEE/RSJ, 1994.
11. P. McKerror. *Introduction to Robotics*. Addison-Wesley, 1990.
12. J. Okada and Y. Toh. The role of antennal hair plates in object-guided tactile orientation of the cockroach. *Journal of Comparative Physiology A*, 186:849–857, 2000.
13. R. A. Russell. Object recognition using articulated whisker probes. In *Intl. Symp. of Intelligent Robotics*, pages 605–11. Tokyo, 1985.
14. J.K. Salisbury. Interpretation of contact geometries from force measurements. In *1st Intl. Symp. on Robotics Research*, pages 565–577. 1983.
15. E.N. Schiebel, H.R. Busby, and K.J. Waldron. Design of a mechanical proximity sensor. *Robotica*, 4:221–227, 1986.
16. John Schmitt, Mariano Garcia, R. C. Razo, Philip Holmes, and Robert J. Full. Dynamics and stability of legged locomotion in the horizontal plane: a test case using insects. *Biological Cybernetics*, 86:343–353, 2002.
17. T. Tsujimura and T. Yabuta. A tactile sensing method employing force/torque information through insensitive probes. In *Intl. Conf. on Robotics and Automation*, pages 1315–20. IEEE, 1992.
18. N. Ueno, M. Svinin, and M. Kaneko. Dynamic contact sensing by flexible beam. *IEEE/ASME Transactions on Mechatronics*, 3(4):254–263, 1998.