Robust Dynamic Locomotion through Feedforward-Preflex Interaction

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ABSTRACT

Unlike most legged robotic systems built to date, even simple animals have the ability to quickly and robustly traverse through rough terrain and over large obstacles and gaps. Recent evidence from insect physiology research indicates that arthropods achieve this fast robust locomotion largely without relying on sensory feedback or reflex response. Instead, locomotion is the result of the interaction between a basic feedforward motor pattern and the visco-elastic properties of the mechanical system, termed "preflexes." In this paper, we consider the implications of this control hypothesis for the design of small running robots for uncertain environments. We present working prototypes that show how robust dynamic locomotion can be achieved without the use of sensory feedback. We then discuss modeling approaches for these kinds of systems and present results from simulations of representative models.

1. INTRODUCTION

Legged locomotion has long been an attractive alternative to wheels or tracks for mobile robots. Legged animals have the ability to negotiate rough terrain and obstacles far more easily than wheeled vehicles of similar size. However, current legged robots enjoy neither the simplicity of wheels nor the versatility of legged animals.

A major difficulty in achieving legged locomotion is to coordinate and control the legs to produce efficient and robust movement of the body. This problem is exacerbated in unstructured environments. One effort to reduce the complexity has been to utilize statically stable locomotion, where the robot's dynamics are assumed negligible. For example, a hexapedal walker may be controlled to maintain the center of mass within a triangle of support formed by three legs. This approach has demonstrated stable locomotion in environments inaccessible to wheeled systems.

However, for legged systems to compete effectively with wheels and tracks, they must become fast. Pioneering research by Raibert (1986) and those who have followed his work (e. g. Koditschek and Buehler, 1991; Schmiedeler and Waldron, 1999; Berkemeier, 1998) has demonstrated that fast locomotion can be achieved in robots by attaining dynamic stability. This dynamic stability implies motion that is stable over time, but which may be statically unstable at any particular instant. These investigations of dynamically stable hopping and trotting robots have illustrated the importance of tuning the compliance of the

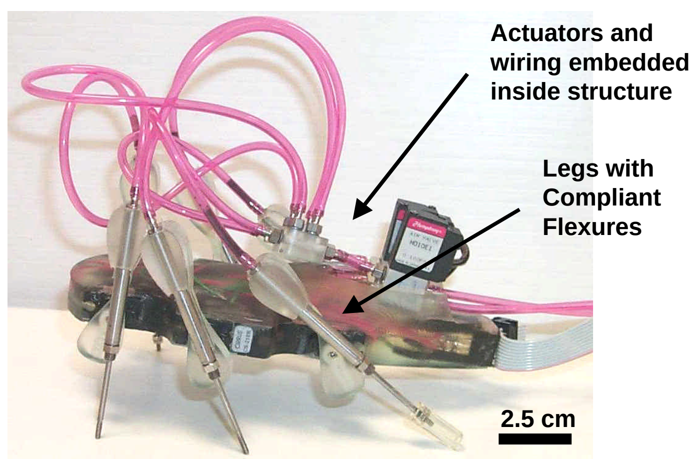


Figure 1. Hexapedal robot constructed using Shape Deposition Manufacturing, capable of robust locomotion at speeds up to 2.5 body lengths per second without utilizing sensory feedback.

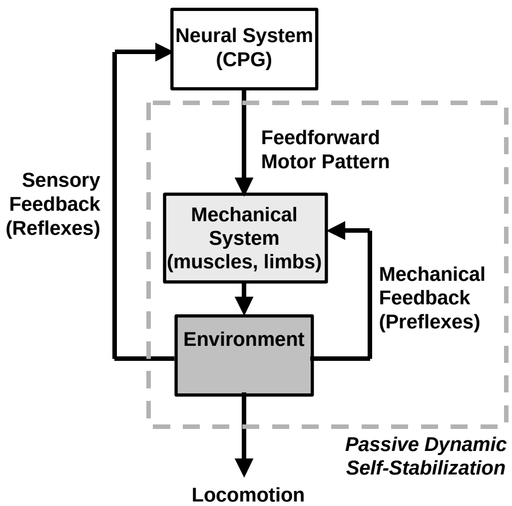


Figure 2. Suggested roles of feedforward motor patterns, preflexes, and sensory feedback. Adapted from Full and Koditschek (1999).

mechanical system itself, in conjunction with simple, but appropriate, feedback control.

Going a step further, we argue that, during fast dynamic locomotion, reliance on sensory feedback (both external and proprioceptive) can compromise the system's robustness. This is especially true as the size of the robot decreases and the system time constants become shorter in comparison to achievable servo rates.

In this paper, we propose systems that achieve robust locomotion through the interaction between a feedforward motor pattern and the properly tuned visco-elastic properties of the mechanical system, properties which have been termed "preflexes" (Brown and Loeb, 1997).

The following section reviews current biological and robotic research that evinces the role of preflexes in locomotion. We then show that such systems are feasible by presenting hexapedal robots that operate without feedback control. These robots, such as the one in Figure 1, can achieve speeds of 2.5 body lengths per second and quickly traverse large, hip-height obstacles. We then consider modeling these types of systems and show that they can result in dynamically stable motion, first analytically for a one-dimensional case and then empirically through simulation of a more complex two-dimensional system. Finally, we discuss ongoing work to further understand the implications of these assumptions.

2. FEEDFORWARD-PREFLEX INTERACTIONS

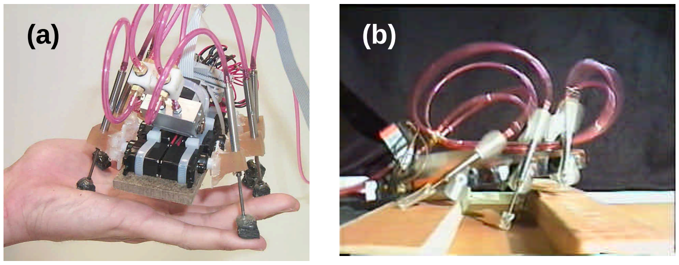
Biological research has found that running animals of different sizes, with different numbers of legs and morphologies, all produce similar patterns of ground reaction forces (Blickhan and Full 1993). These ground reaction forces are often thought of as being produced by a virtual spring-mass system, or a "bouncing monopod." Full and Koditschek (1999) suggest that this simple behavior is in fact the target behavior of redundant multi-legged systems that possess many degrees of freedom. Indeed, the fast and dynamically-stable locomotion in Raibert's and related robots have as their basis the simple model of a spring-loaded inverted pendulum. Even Raibert's two and four-legged systems operated by exploiting symmetry and by coordinating, through control, the many degrees of freedom available to behave as a single virtual leg. While this revolutionary work showed that fast dynamically-stable locomotion can be achieved through this simple model, the issue of robustness has received less attention. Here we define robustness as the rapid convergence to a desirable steady-state behavior despite extreme, unexpected disturbances or changes in terrain.

Although different animals utilize different strategies for traversing rough terrain, we draw particular inspiration from the robust performance of small arthropods. Full has shown that the cockroach *Blaberus discoidalis* can scramble over a fractally-distributed collection of obstacles up to three times its body height (Full et al., 1998). They do this without flipping over or even appreciably slowing down.

Moreover, it has been observed that during locomotion through this rough terrain, the basic motor pattern sent to the muscles did not notably change. There is no precise foot-placement, no follow-the-leader gait. For small animals like the cockroach, the effects of disturbances are immediate relative to the stride period (Ting et al., 1994). Delays in the sensory feedback loop used in reflexes can be compromising. Thus, it appears the cockroach creates robust locomotion through a basic feedforward pattern applied to its mechanical system, relying on very little, if any, sensory feedback during a stride.

This extreme exclusion of sensory feedback in such uncertain environments can only be possible through an appropriately designed mechanical system on which the feedforward pattern is applied. Without some kind of disturbance rejection, perturbations would quickly drive the system astray. There is evidence that self-stabilization comes from preflexes, the non-linear, passive visco-elastic properties of the mechanical system itself (Brown and Loeb, 1997; Meijer and Full, in press). The mechanical nature of these preflexes makes their response instantaneous, of zero order, allowing the system to rapidly respond to disturbances.

An example of these preflexes in robots is the compliant air-spring in the leg of Raibert's robots. Compliance was shown to be a necessary, simple, and efficient way to carry out the energy exchanges between kinetic and potential energy present in running or hopping. More recent work has shown that the configuration of the mechanical system itself can determine passive stable behavior (Kubow and Full, 1999). In addition, ongoing research seeks to determine the role of passive damping found in the joints and exoskeleton of insect legs



(c)

	Mini-Sprawl	Sprawlita
Mass	.250 Kg	.270 Kg
Dimensions	12x14x12 cm	16x10x9 cm
Leg Length	4.5 cm	4.5 cm
Stride Period	350 ms	200 ms
Max. Speed	25 cm/s	39 cm/s
	2 body/s	2.5 body/s

Figure 3. Hexapedal Prototypes. (a) Mini-Sprawl was built with a compliant coupling between the pistons and the servos. (b) Sprawlita, here shown traversing through hip-height obstacles. (c) Table showing general dimensions and performance of the prototypes

during locomotion (Xu et al., 2000). It is estimated that the limbs of the cockroach are approximately critically damped (Garcia and Full, unpublished).

This interaction between feedforward patterns and preflexes is believed to be an appropriate control scheme for creating robust repetitive motion, such as locomotion (Kuo, 1998; Full and Koditschek, 1999). The relative roles of feedforward, sensory feedback and preflexes in organisms have been hypothesized as illustrated in Figure 2. Slow movement can rely on sensory feedback for active stabilization and precision, where delays are tolerable. Fast repetitive movement must rely on rapid-acting, passive self-stabilization.

The possibility of creating fast robust locomotion without relying on sensory feedback has interesting implications for legged-robot design. The simplicity of control resulting from these types of systems is very attractive, as sensor noise and delays are no longer concerns.

The challenge now becomes the careful design of the mechanical system, such that it possesses the appropriate self-stabilizing properties that work in concert with the feedforward pattern. This difficulty can be seen in the scarcity of dynamic robots that exhibit robust performance comparable to that observed in *Blaberus discoidalis*. Extending the theoretical monopedal robustness results to multi-legged robots remains an active research problem. Most of the results in this area have made restrictive assumptions regarding symmetry and leg coupling.

Of course, the creation of robust dynamic robots for basic locomotion will require more than just tuning the passive

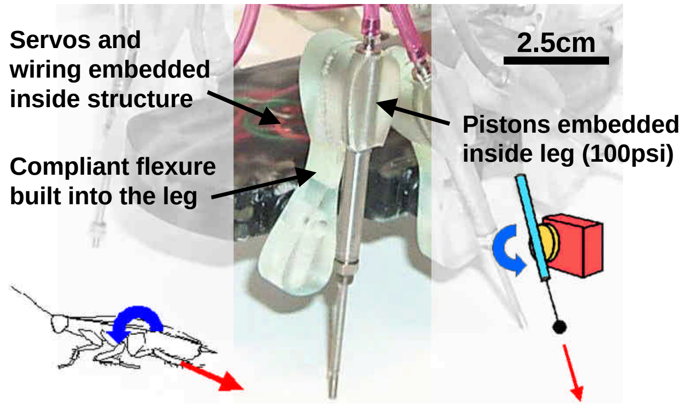


Figure 4. Close-up of robot manufactured by SDM. Leg design was based on cockroach kinematics and studies of leg function, which indicate that legs act as thrusters without relying on high hip torques. The robot was built with thrusting pistons connected to rotary servos through a compliant hip flexure.

mechanical properties to respond to a feedforward pattern. Just as important are the sprawled posture and multiple legs, for instance, which play a significant role when negotiating rough terrain. Here, leg design, kinematic arrangement and function contribute to self-stabilization. Obviously, physical sturdiness allows the cockroach to survive collisions due to extreme terrain irregularities.

In the following section, we present prototypes we have built which capitalize on all of these factors for robust locomotion.

3. HEXAPEDAL PROTOTYPES

The prototypes presented here are initial attempts at combining several of the hypotheses mentioned above concerning robust locomotion. While much work remains to understand the relative roles of these design principles, the surprisingly robust performance of these and other prototypes (Saranli et al., 2000) helps validate and motivate this general approach. Thus, our prototypes are presented here merely as existence proofs that the combination of a feedforward pattern with a properly tuned and designed mechanical system can lead to the creation of fast robust robots.

Figure 3a and 3b show two of our prototype hexapedal robots. The first, "Mini-Sprawl", was assembled by traditional means. The second, "Sprawlita," was constructed using Shape Deposition Manufacturing (SDM), an emerging layered-manufacturing technology (Bailey et al, 1999; Cham et al, 1999; Rajagopalan et al., 1999; Merz et al, 1994). As shown in Figure 4, SDM allowed us to embed the actuators, wiring and connectors into the structure of the robot itself, increasing sturdiness by avoiding the unreliability of traditional fasteners and connectors. In addition, SDM permits the fabrication of parts with spatially varying material properties. In this prototype, the compliance properties of the leg were varied by using a soft grade of polyurethane in specific locations.

Figure 3c shows the general dimensions of the prototypes as well as approximate maximum speeds on a flat surface. The scale of surface variations for which we've observed locomotion without significant loss of speed is illustrated in Figure 3b. These variations were as large as the lengths of the legs themselves. The maximum speed obtained by Sprawlita was approximately 0.39m/s, roughly equivalent to 2.5 body lengths per second or 8 leg-lengths per second.

Instead of directly mimicking the kinematics of the cockroach, the design of the prototypes is based on observations of leg function in the sagittal plane of the cockroach. Leg design is as shown in Figure 4, and consists of a pneumatic piston attached to a servo through a compliant coupling. This configuration is based on the observation that legs act as thrusters during locomotion, as indicated by measurements of cockroach ground reaction forces (Full et al., 1991). The legs are placed such that the center of mass lies towards the back of the robot. The nominal angles of the legs are determined by the servos such that each leg performs a different function. As observed in arthropods, front legs are angled forward to act as decelerators and back legs are angled backwards to function as accelerators (Full et al., 1991).

The feedforward pattern applied to this mechanical system is simple. Two three-way valves are activated at a stride frequency. Each valve controls air into the three pistons corresponding to one tripod of support. The duty cycle of each tripod, the percentage of the stride period in which air is supplied to the pistons, determines the relative phase and the amount of overlap between the two tripods. In the first prototype, Mini-Sprawl, the servos are commanded to swing back and forth during the each tripod's activation period. Higher compliance was designed into the hips of Sprawlita, resulting in comparable speeds even without active servo movement. That is, the leg's swinging motion can be solely due to the passive compliance at the hip.

The role of compliance is emphasized by these prototypes. An earlier version of Mini-Sprawl with non-compliant hip joints was not able to move forward at all. In addition, changes in the nominal angles of the hips, controlled by the position of the servos, can cause significant changes in the speed and direction of locomotion. For example, turning on flat terrain could be effected in Mini-Sprawl by making the angles of the legs of one side of the robot more extreme. This same behavior has been hypothesized for the cockroach, where variations in leg placement are believed to initiate rapid turning (Jindrich and Full, 1999).

The ability of these prototypes to quickly traverse large surface variations demonstrates that robust locomotion is possible through a combination of feedforward/preflex control, appropriate leg design and manufactured physical sturdiness. However, we have yet to fully characterize the exact roles

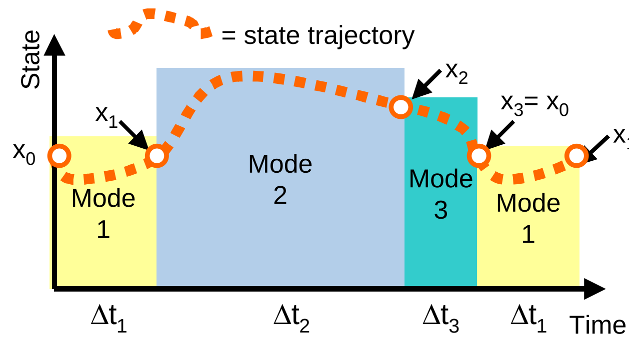


Figure 5. In the simplified systems considered here, mode transitions occur at scheduled times, as given by by the feedforward pattern. The condition for a periodic orbit is that the state repeats itself after a complete cycle.

played by each of these principles. Indeed, the performance obtained from these prototypes is the result of experimental design iterations in which parameters such as leg angles, stride frequency, location of center of mass and duty cycle were varied to maximize the robot's speed.

The following section presents a modeling approach to these feedforward-controlled compliant systems. Through these models, we hope to gain better understanding of the basic mechanisms underlying the type of locomotion these systems are evidently capable of.

4. MODELING FEEDFORWARD-PREFLEX SYSTEMS

Locomotion can be modeled as a sequence of modes and transitions between modes. Each mode represents a different configuration of the mechanical system, possibly under some control law. For example, as each alternate leg or set of legs is placed on the ground, the system transitions from one mode to another. Modeling used in statically-stable walking, passive-walking and dynamic hoppers research follows this general approach (McGeer, 1990; Koditschek and Buehler, 1991). In Raibert's hoppers, for example, locomotion was described as transitions between a flight phase, a compression phase, a thrusting phase and a decompression phase (Raibert, 1986).

Transitions between modes are generally determined solely by events in the state of the system. For example, a passive walker changes mode when the foot contacts the ground, and a Raibert hopper initiates a thrusting mode when the extension rate of the leg changes sign. However, for the systems considered here, a different approach is taken.

In the systems considered here, we first assume that mode transitions can be initiated by the feedforward pattern. For example, leg activation in our prototypes is a predetermined function of time as given by the frequency and duty cycle with which the solenoid valves are powered. This given, we assume that in steady-state locomotion, foot contact occurs after an approximately fixed time delay after the valves are commanded.

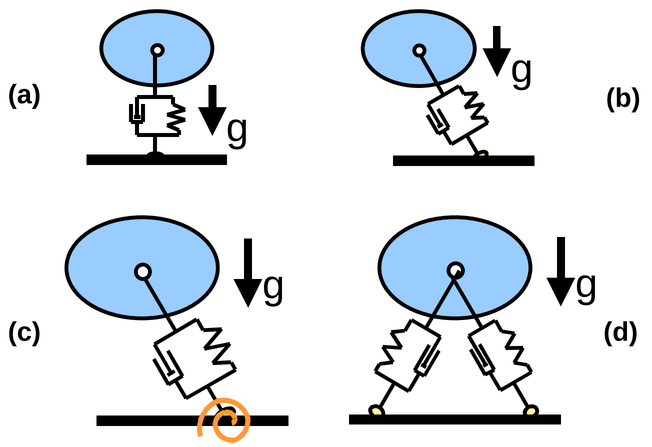


Figure 6. The four different simple models considered: a) 1 DOF hopper b) 2 DOF with compliant swinging leg c) 2DOF with compliant leg and foot spring d) 2 DOF with two compliant swinging legs

We assume that any variations in these foot contact delays are small compared to the stride period. By neglecting this variability, we can assume that mode transitions can occur as a known function of the feedforward pattern alone.

Furthermore, we restrict our analysis to locomotion in which the posture of the robot is such that ground contact is maintained at all times without a flight phase. This type of running, termed “Groucho” running (McMahon, 1987), is observed in most insects (Ting et al., 1994). Without a flight phase, and neglecting variability in foot contact, mode transitions are completely determined by the feedforward pattern. Mode transitions can be considered “scheduled,” as shown in Figure 5, and are not dependent on sensory feedback. Terrain irregularities which alter this schedule in any way simply result in disturbances at the initiation of the next mode.

The prototypes presented in the previous section represent simplified abstractions of the actual cockroach that capture the same basic locomotion capabilities. Despite their distilled nature, even exact models of these prototypes are still too complex to determine trends and draw conclusions about why these locomoting systems work in general.

In order to capture the basic behavior of these “scheduled” systems, we first start with a simple analytical 1 DOF model to reveal some general properties. From this simple model, we increase the complexity of the model until we arrive at an appropriate model that captures the basic mechanisms required for robust locomotion through feedforward. Simulations of this model reveal basic design principles and trade-offs inherent in these systems.

4.1. One Degree-of-Freedom Motion

As a starting point for the discussion of modeling approaches, we first consider the simple example of a one-degree-of-freedom mass-spring-damper system, as shown in Figure 6a. Next, assume that the system transitions between n modes at given times within a cycle period according to a predetermined pattern. Each mode is defined by a different set of values for the damping coefficient, spring constant and equilibrium point of the spring. Note that a mode transition can occur which creates an instantaneous compression or decompression of the spring.

Integration of these linear, time-invariant systems yields the following trajectories for each of the modes:

$$x_i(t) = e^{A_i t} x_i(0) + (I - e^{A_i t}) x_{eq-i} \tag{1}$$

$$i = 1, 2 \ldots n$$

where $e^{A_i t}$ is the state-transition matrix and $\tilde{x}_{eq-i}$ is the equilibrium point of the mass-spring-damper system of mode i. The general conditions for a cycle are:

$$\begin{aligned} x_1(0) &= x_n(\Delta t_n) \\ &\ldots \\ x_n(0) &= x_{n-1}(\Delta t_{n-1}) \end{aligned} \tag{2}$$

where Δt_n is the duration of mode n. Combining Eq.1 with Eq. 2 produces:

$$\begin{aligned} x_1(\Delta t_1) &= e^{A_1 \Delta t_1} x_n(\Delta t_n) + (I - e^{A_1 \Delta t_1}) x_{eq_1} \\ &\ldots \\ x_n(\Delta t_n) &= e^{A_n \Delta t_n} x_{n-1}(\Delta t_{n-1}) + (I - e^{A_n t}) x_{eq_n} \end{aligned} \tag{3}$$

Given the properties of the modes of the system and their duration, we can solve the linear system above for the states at the mode transitions $x_i(\Delta t_i)$. These states at the transitions define the periodic trajectory, or orbit, of the system. One way to view this orbit is as the motion created by changing the equilibrium point of the system at each mode.

The existence of this orbit does not depend on the stability of each of the modes. That is, a periodic orbit may still exist, despite the fact that all of the individual modes are unstable.

The robustness of this orbit may be studied by looking at the response to a perturbation from the nominal orbit. It can be shown that a perturbation $\tilde{x}_{n,k}$ at the end of mode n will map into a perturbation $\tilde{x}_{n,k+1}$ at the next complete cycle as follows:

$$\tilde{x}_{n,k+1} = e^{A_n \Delta t_n} \ldots e^{A_2 \Delta t_2} e^{A_1 \Delta t_1} \tilde{x}_{n,k} = M \tilde{x}_{n,k} \tag{4}$$

From discrete linear systems theory, a perturbation will eventually decay if the eigenvalues of the product of the state-transition matrices, M, have magnitudes less than unity. Thus, the robustness of the periodic orbit to perturbations is given by

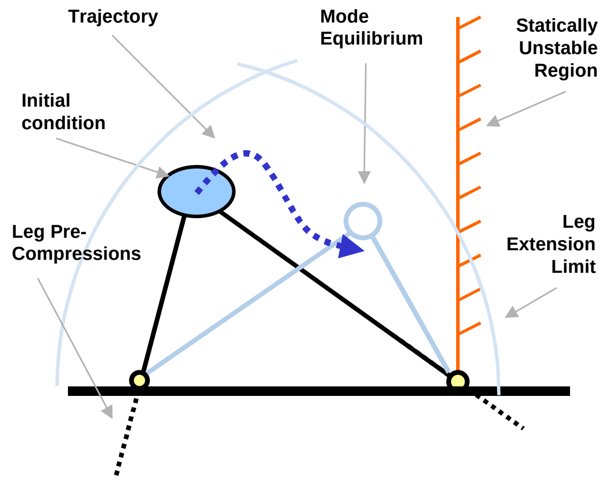


Figure 7. Conceptualized trajectory of sprawled-posture model. Model parameters can be chosen to modify the trajectory within the duration of the mode.

the magnitude of these eigenvalues.

It can be shown that the largest eigenvalue of M is at most the product of the largest eigenvalues of the individual state-transition matrices. In summary, a periodic orbit may be obtained through any combination of stable and unstable modes. However, the robustness of this orbit to perturbations is dependent on the aggregate effect of these modes.

Of course, this 1 DOF system is a very limited case on which to draw conclusions about this class of systems. However, the observations made above will guide our exploration of systems with higher degrees of freedom.

4.2. Two Degrees-of-Freedom Motion

We now consider motion restricted to the sagittal plane, treating the body as a point mass such that there are only two degrees of freedom. Our goal is to arrive at a simple model which operates under a feedforward pattern and captures the same mechanism for locomotion as that observed in biology and our prototypes.

An alternative 2 DOF system is the spring-loaded inverted pendulum, shown in Figure 6b. This "hopper" model exhibits the essential motion and ground reaction forces seen in many locomoting systems when running over flat ground (Blickhan and Full 1993). However, we believe this model does not capture the important stabilizing role played by sprawled posture in cockroaches. While locomotion orbits can be achieved with this unstable model, robust operation is completely dependent on feedback. Like the 1 DOF example considered earlier, an orbit is possible using feedforward alone even when transitioning between unstable modes, but at the cost of extreme sensitivity to disturbances.

More complex models which begin to capture the self-stabilizing role of sprawled posture are shown in Figures 6c and

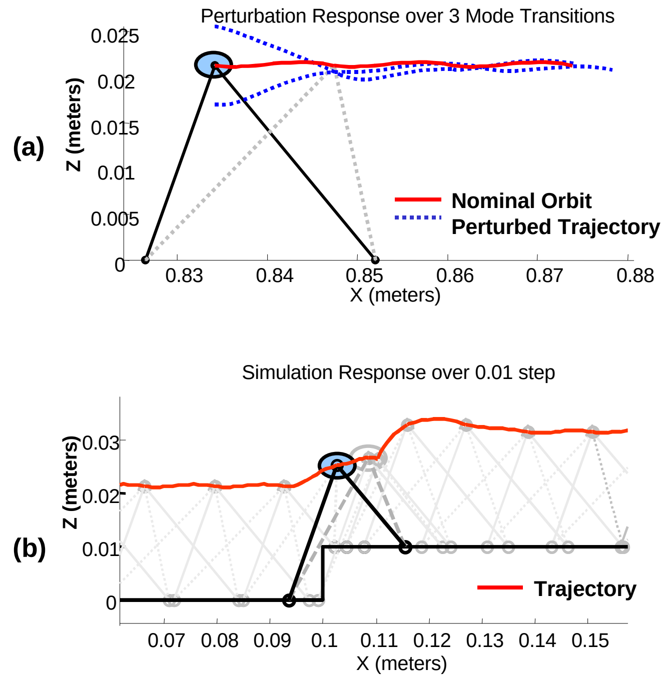


Figure 8. a) Simulation response of the system to vertical perturbations. b) Simulation response with increase in terrain height. Our measure of "robustness" is an indication of how rapidly the system converges to its original trajectory after such disturbances.

6d. In these models, there can exist a stable equilibrium point within each mode, a property which we believe should be exploited in robust locomotion. As we will show next, moving this equilibrium point between modes according to a feedforward motor pattern is a useful way to create robust motion, similar to the 1 DOF example discussed earlier.

We choose to start with the model shown in Figure 6d because the effects of varying parameters is more intuitive. In the model, a set of legs placed on the ground is represented by two damped, compliant legs. The role of the front leg is to decelerate the body, while the role of the back leg is to create forward thrust. Moreover, since we are only considering motion in the sagittal plane, the alternate set of legs is identical to the first. If we assume duty cycles of 50%, then there is only one effective mode, which is reset at half the stride period.

Figure 7 shows the basic configuration of the system during one half-period. At the beginning of the mode, each leg is reset to a prescribed angle relative to the body. The location of the mass at the moment of transition may be such that the leg is precompressed when it is set down. The system will then have a trajectory given by its initial conditions that will move forward towards the equilibrium position of that mode. The mode is then switched, or reset, and the cycle begins again, resulting in forward locomotion.

Simulation of this system shows that, given appropriate parameters, motion of the system converges to a given orbit, as shown in Figure 8, despite perturbations and terrain changes. Moreover, we can use the Floquet Technique (Sastry, 1999) to estimate how rapidly it will recover from disturbances. Perturbations to fixed points on the nominal orbit are approximately mapped from one cycle to the next as follows:

$$x_{n,\,k+1} = f(x_{n,\,k}) \tag{5}$$

$$\bar{x}_{n,\,k+1} = \left.\frac{\partial f}{\partial x}\right|_{x_{n,\,k}} \bar{x}_{n,\,k} = M\bar{x}_{n,\,k} \tag{6}$$

Where *f*, termed the return-map of the system, is the function which maps the state from one cycle to the next. In this case, the non-linearity of the equations of motion does not permit analytical integration. Instead, this function is found by numerical integration and the derivative above is found by computing the sensitivity matrix about the fixed point on the nominal trajectory. At mode transitions, the legs are placed relative to the body, making x-position perturbation analysis inappropriate. Hence, these perturbations are not considered in the computation of the matrix *M*. Similar to the 1DOF case, the magnitude of the eigenvalues of this matrix *M* indicate the local robustness of the orbit.

This measure of robustness and the diagram in Figure 7 suggest a set of general design principles with which to choose the many parameters in this system. Although the relationships between all of these parameters are highly complex, various parameters will influence certain aspects of the resulting motion. The stiffnesses and nominal lengths of the legs and the angles between them can be chosen to modify the equilibrium point. The initial angle of the legs with respect to the body can be selected to locate the initial configuration with respect to the equilibrium point. The amount of damping in the legs influences the rate at which the body moves towards the equilibrium point. Finally, the duration of the mode affects the length of the trajectory before the next mode transition.

As an example, parameter studies through simulation indicate that there is a general trade-off between locomotion speed and the local robustness of the nominal orbit. Figure 9 shows the robustness of a given orbit as a function of the damping in the model legs. Robustness is approximated as the inverse of the magnitude of the largest eigenvalue of M, as given by Eq. 6.

In general, higher speeds are obtained by expanding the trajectory of the body within a mode. This can be achieved by a combination of decreasing the damping in the legs, extending the mode duration time, placing the equilibrium point towards the front and placing the initial condition towards the back. However, this places the trajectory closer to the limits of the statically-stable regime, given by the footholds, thereby compromising robustness. Interestingly, the center of mass of cockroaches during fast locomotion also approaches the limits of the triangle of statically-stable support (Ting et al., 1994).

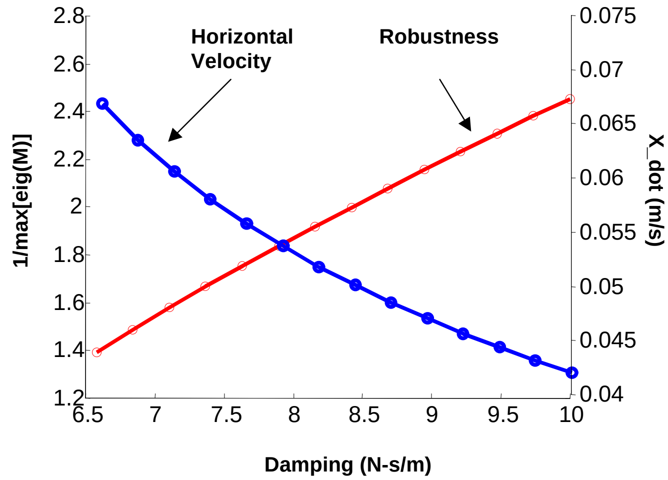


Figure 9. Effects of increasing damping in the legs of the model in Figure 6d. Velocity can be increased, but at the expense of robustness to perturbations

The simplified models presented above are used only to increase our understanding of the type of system that we believe approximates the behavior of our prototypes. As shown, these systems are characterized by: 1) motion towards an equilibrium configuration given by the passive properties of the mechanical system and 2) a feedforward pattern that increments the location of this equilibrium configuration to obtain forward locomotion.

5. CONCLUSIONS AND FUTURE WORK

While the relative roles of feedforward and feedback during fast locomotion through unstructured terrain are yet to be fully determined, the possibility that much of the motion and robustness can be achieved without sensory feedback is indeed attractive. Especially at small scales, reliance on sensors becomes cumbersome as smaller mechanisms become harder to instrument and the time constants of the physical system decrease in comparison to achievable servo rates.

The prototypes presented here indicate that without sensory feedback, but with a properly designed mechanical system, legged robots can achieve dynamic performance in rough terrain that begins to compare with that seen in nature. The modeling approach proposed is only a starting point for our understanding of the mechanisms that make these systems work so well. Future work will focus on further analysis of these models and on determining the ways in which these simplified models can map to the more complex systems of the robot prototypes.

As shown, the function of sensory feedback appears to be minimized during fast repetitive motion. However, we are investigating the ways in which feedback can be used at a higher level to alter the feedforward motor pattern or other characteristics of the system in order to adapt to changing conditions.

Finally, we advocate that biomimetic behavior must be combined with biomimetic physical structures if these robots are to become truly robust. To this end, we continue to integrate biological findings from insect physiology with the nascent capabilities of Shape Deposition Manufacturing to develop robot structures with properly tuned mechanical properties and integrated sensing and actuation.

ACKNOWLEDGEMENTS

Special thanks to the members of the U. C. Berkeley PolyPEDAL Lab for their enthusiasm, open communication and technical contributions to this work. The authors also thank the members of the Stanford CDR and RPL teams for their contributions to the work documented in this paper, especially Jonathan Clark for his role in building Sprawlita. Sean Bailey is supported by an NDSEG fellowship. This work is supported by the National Science Foundation under grant MIP9617994 and by the Office of Naval Research under N00014-98-1-0669.

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