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Adapting Work Through Actuator Phasing in Running

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Abstract

Actuator phasing can play a significant role in the dynamics of running. Actuator phasing refers to the timing of the activation and deactivation of the actuators relative to the motion of the system. Most previous analyses of running systems have either focused on conservative models of running (with only springs in the legs and no actuators) or on models based on Raibert's hoppers [1], in which leg thrust is activated at one particular instant in the locomotion cycle. Using a simplified monopod model, the analysis presented in this paper reveals that there are significant advantages, in terms of efficiency and forward speed, to activating thrust at other points in the system's trajectory. The timing of actuator activation and deactivation is shown to have a direct effect on the amount of work performed by the actuators. Taking advantage of this role in regulating system energy, we first show that varying the time that thrust is activated can be used to stabilize the running monopod. We then demonstrate how monitoring actuator phasing can be used for the adaptation of stride period in an experimental hexapedal running robot. These results lead to the general idea that subtle changes in the timing of actuation can have a significant impact on dynamic movements such as running, and can be utilized for control and adaptation.

1. Introduction

Fast and robust running is possible with little or no active sensory feedback. The Sprawl family of hexapedal robots developed in our laboratory [2], shown in Figure 1, have demonstrated that a simple mechanical system with properly designed passive properties can be controlled open-loop to achieve significant speed and obstacle clearance. Recent results have demonstrated speeds of over 5 body-lengths per second on flat terrain, and the ability to overcome hip-height obstacles without significantly slowing down or altering course.

Although stable behavior is possible in the Sprawl robots for a range of open-loop parameters, the resulting performance can vary in terms of forward speed and the ability to reject disturbances. In particular, changing the stride period of the motor pattern (the time between activations of the actuators) can have a significant effect on stride length and forward velocity. It is observed that as the stride period is changed, the phasing of the actuator motor pattern relative to the motion of the system changes. This phasing of the actuators can be characterized by the timing of thrust activation and deactivation relative to an event in the locomotion cycle, for example the instant that landing occurs and the legs touch the ground.

Thus, we are motivated to understand the role that actuator phasing plays in running systems like our robots. This inquiry leads to the general question of when in the locomotion cycle should actuation be initiated and terminated for maximum performance. This question is applicable not only to systems controlled open-loop such as our robots, but to a general class of running systems in which energy input can take place at different points in the locomotion cycle, as either a function of sensory input or a predetermined motor pattern.

The approach taken analyzes a simplified model of locomotion in the sagittal plane. The model is a modified version of the Spring-Loaded Inverted Pendulum (SLIP) often studied in analyses of running systems [3][4][5]. This model consists of a point mass constrained to move in the plane attached to a spring-loaded massless leg. The model studied here, shown in Figure 2, has the following distinguishing features: the inclusion of significant damping (damping ratio of 0.2), and the variation of the instant of activation of thrust. Both the damping and thrust-producing elements are in parallel with the spring in the leg. Most previous analyses of running systems using simplified models have either ignored damping (see for example

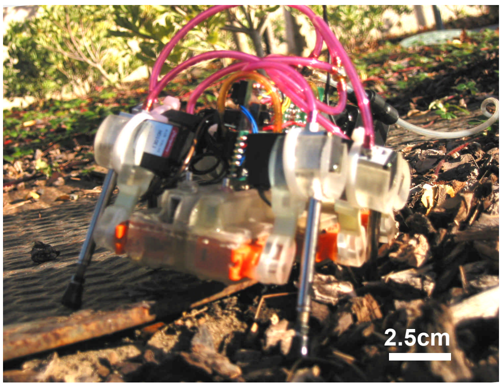

Figure 1. Although the Sprawl family of robots can achieve robust locomotion without sensory feedback, the ability to transition effectively between different types of terrain will require adaptation of the open-loop parameters.

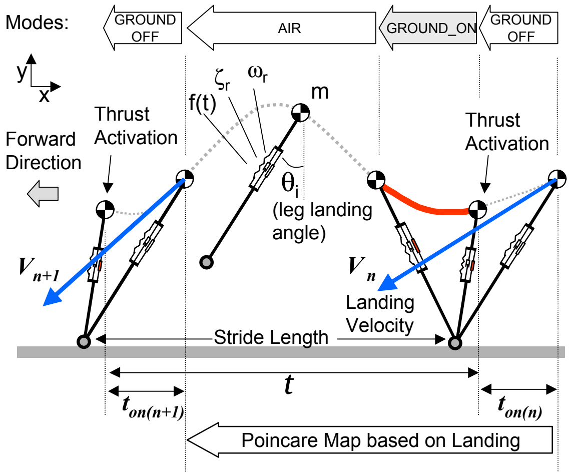

Figure 2. Simplified monopod model. A Poincare Map is formed at the instant that the leg lands on the ground.

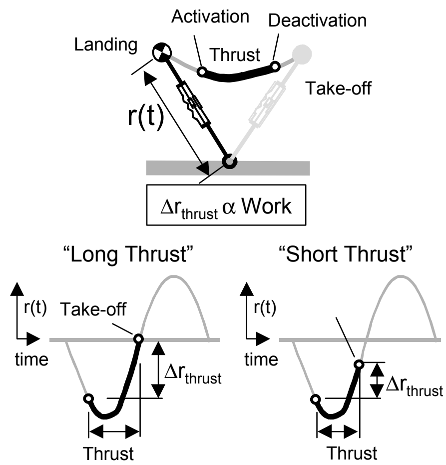

Figure 3. Work performed by the actuator can be characterized by the timing of thrust activation and deactivation.

[6]), or assume the control method originated by Raibert, in which thrust is activated when the leg reaches maximum compression (see for example [7]).

Both damping and variations in actuator phasing can play important roles in running. Viscoelastic properties such as damping are not only inevitable in real systems but have been found to contribute significantly to self-stabilization in animals [8][9]. As shown in this paper, varying the phasing of thrust actuation provides a heretofore unexplored "knob" for "tuning" running behavior that has a large impact in the resulting performance, in terms of efficiency and forward velocity. Variations in actuator phasing can also be used to stabilize the monopod in closed-loop, and to adapt the motor pattern in systems like our hexapedal robots that are able to run stably without feedback.

The following section describes the model in more detail and establishes the relationship between work and actuator phasing. We then relate work to performance in Section 3 by examining the continuum of steady-state trajectories of the system that arise when thrust activation is varied. In Section 4, the influence of varying thrust timing on the motion of the monopod is used as the basis for a proposed alternative to Raibert's "neutral-point" foot-placement controller for stabilizing a monopod. In Section 5, the established relationship between work and actuator phasing is used in the slow-rate adaptation of stride period in our hexapedal robots. Finally, we present conclusions in Section 6.

2. Work and Actuator Phasing

The planar model of running is shown in Figure 2, and consists of a point mass attached to a massless leg with a spring and a damping element such that the system has a natural frequency ω_r and damping ratio ζ_r. The spring has a nominal rest length of r_0. The coordinates x and y are normalized by the mass and by gravitational acceleration. A force-producing element, $f(t)$, is in parallel with the spring and damper, and applies a normalized constant force f when activated. The runner goes through a series of "modes" as it comes into and out of contact with the ground, each described by its own set of differential equations, as shown in the figure. In this idealized model, the leg is automatically reset to a landing angle θ_i with respect to the vertical while in the air. The leg comes into contact with the ground when,

$$y < r_0 \cos(\theta_i) \tag{1}$$

where y is the height of the mass measured relative to the floor. The location where the leg contacts the ground determines the location of the leg's pointed foot for the rest of the stance phase. The hopper takes off when the distance from the mass to the foot exceeds r_0.

Without having to solve the model's differential equations, we can characterize the work performed by the actuator during the stance phase by looking at the length of the leg, r, at thrust activation and deactivation. The work performed is equal to the integral of the product of the force times the rate of change of the leg length:

$$\int_t^{(t+\tau)} f(t) \cdot \dot{r}(t) dt = WorkInput \tag{2}$$

where $r(t)$ is the length of the leg and τ is the stride period. If $f(t)$ is a square wave of magnitude f that is activated at t_{on} and terminated at t_{off}:

$$f \cdot \int_{t_{on}}^{t_{off}} \dot{r}(t) dt = f \cdot (r(t_{off}) - r(t_{on})) \tag{3}$$

This implies that the net work performed by the actuator is proportional to the difference in leg length between thrust activation and thrust termination:

$$r(t_{off}) - r(t_{on}) = \Delta r_{thrust} \propto WorkInput \qquad (4)$$

As illustrated in Figure 3, the conditions for maximizing this work depend on when deactivation of thrust occurs relative to take-off. In situations termed “Long Thrust,” deactivation of thrust is set to occur after take-off such that thrust is actually terminated by the leg reaching maximum extension. In these situations, the work performed by the actuator is maximized when thrust activation occurs when the leg reaches maximum compression, as illustrated in Figure 3. In this case, activating thrust before maximum compression results in negative work done to slow the system down, while activating after maximum compression reduces the amount of positive work performed. For situations in which thrust duration is limited (termed “Short Thrust”), and deactivation occurs before take-off, the work performed is not maximized when thrust activation occurs at maximum compression. Rather, work is maximized when deactivation occurs near the instant of take-off, which may be accompanied by activation occurring after maximum compression. Thus, given a short thrust duration, the Raibert approach of activating thrust at the leg’s maximum compression is suboptimal in terms of maximizing the net work performed by the actuator.

Having characterized the work performed by the actuator, it remains to be seen whether maximizing work corresponds to maximizing metrics of interest such as stride length and forward velocity. This is addressed in the next section.

3. Performance and Actuator Phasing

In order to analyze the effect of actuator phasing on performance, we focus our study on period-1 steady-state trajectories of the system, which are trajectories that repeat themselves after one cycle of locomotion. Such steady-state trajectories are found by formulating a Poincare Map, which maps the state at a particular event in the locomotion cycle to the same event in the next cycle [10]. For the case of the running model studied here, we must also restrict our study to trajectories that go through a particular sequence of modes. The sequence of modes studied is defined as “Long Thrust”, and corresponds to activating thrust until take-off. Results for the sequence of modes that corresponds to “Short Thrust,” in which thrust is deactivated before take-off, are assumed to be similar in terms of the effect of the work performed by the actuator on performance.

A Poincare Map is chosen about the instant that landing occurs. This map is a function M that, given

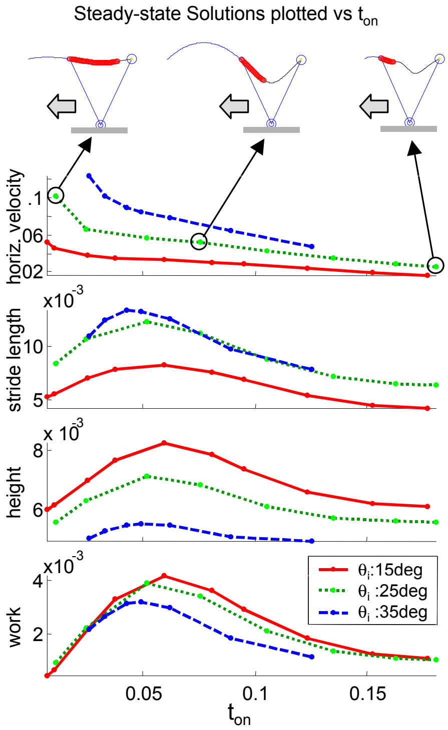

Figure 4. Steady-state solutions as a function of t_{on}, the time after landing that thrust is activated.

the magnitude $|V|_{(n)}$ and direction $\theta_{V(n)}$ of the velocity of the mass at landing, returns the magnitude and direction of the velocity at the next landing:

$$(\theta_{V(n+1)}, |V|_{(n+1)}) = M(\theta_{V(n)}, |V|_{(n)}) \qquad (5)$$

It is assumed that the time t_{on} after landing that thrust is activated is a constant, and that the leg landing angle θ_i is also a constant. Steady-state trajectories are found by solving the steady-state constraint:

$$(\theta_V^*, |V|^*) = M(\theta_V^*, |V|^*) \qquad (6)$$

Where $(\theta_V^*, |V|^*)$ represents the steady-state solution and is called the “fixed point”. Since the equations of motion for the model are non-linear, the function M is implemented as a dynamic simulation using Matlab (The Mathworks, Inc.). Steady-state solutions were found for given values of ω_r (ω_r=30), ζ_r (ζ_r=0.2) and f (f=1.2) by first choosing a value for the landing angle θ_i, then solving Equation 6 numerically for a range of values of t_{on}. Varying t_{on} allows us to find solutions other than the ones in which thrust is initiated at maximum compression. Once a solution has been found, the following quantities are measured from the steady-state trajectory: the horizontal velocity, stride length, maximum height and the work performed by the actuator. Figure 4 shows the solutions found in terms of the quantities measured plotted against t_{on} for several landing angles.

Before analyzing these results, it is worth noting that when these quantities are plotted against the stride period of each particular solution, the plots "fold" on themselves, resulting in multiple steady-state solutions for a given stride period. This can have serious consequences if thrust is activated open-loop according to a fixed motor pattern, as multiple behaviors are possible for a given period of the motor pattern. This loss of control over the resulting behavior is a drawback of open-loop control of running, as reported in [11].

As illustrated by the corresponding sample hopper trajectories at the top of Figure 4, the continuum of steady-state solutions spans trajectories in which thrust is initated shortly after landing to trajectories in which thrust is initiated well into the stance phase, such that motion in the radial direction has started to settle.

The figure shows that forward velocity is a monotonically decreasing function of t_{on}, and is maximized for low values of t_{on}. This indicates that solutions in which thrust is initiated shortly after landing, here termed "skittering" solutions, are more optimal in terms of horzontal velocity for a given leg landing angle than solutions in which thrust is initated at maximum compression. By initiating thrust early, these "skittering" solutions are able to sustain a large horizontal landing velocity in steady-state by supporting the mass without significant leg compression, in a motion that is similar to "vaulting" with a stiff pole. The figure also shows that these solutions do not have the highest stride length (distance covered per stride), but due to the shorter stride period, and thus higher stride frequency, the solutions have higher horizontal speeds.

While speed is maximized by activating thrust shortly after landing, stride length is maximized in solutions in which thrust is initiated near maximum compression of the leg. This is attributed to a corresponding maximum amount of work performed by the actuator, resulting in a large take-off velocity. Leg landing angle has a significant effect on speed, as shown also in Figure 4. Increasing the landing angle increases speed and stride length, and decreases the hopping height. Steady-state solutions could not be found for leg landing angles of 40 degrees and higher, indicating that while speed is increased with leg angle, there is a limit for which steady-state motion will exist.

From Figure 4, note that changing the leg angle significantly changes the value of t_{on} for which stride length is maximized. However, this value of t_{on} maintains correspondence with the value of t_{on} for which work is maximized. This interesting result indicates that "tuning" the actuator phasing such that maximum work is performed finds the value of t_{on} which optimizes stride length, regardless of the leg landing angle. This suggests that actuator phasing can be tuned independently of system configuration, as long as it is tuned for maximum work, and that it will result in the optimal stride length for each particular configuration.

These results show that by varying the instant in the cycle that thrust is activated, a range of running trajectories not previously considered is revealed, and that hopping behavior can vary significantly within this range. For example, the same horizontal velocity achieved by using a large leg landing angle and thrusting at maximum compression can also be achieved by using a smaller leg landing angle and thrusting before maximum compression. The first configuration could be useful in situations where high ground clearance is needed, as the resulting trajectories also maximize hopping height. The second configuration would be advantageous in situations where ground traction is critical, as large landing angles could result in slippage.

4. Actuator Phasing in Stabilization

The above results are based on steady-state trajectories of the running model, and are applicable regardless of whether the leg landing angle or thrust activation are controlled closed- or open-loop. We now consider the stability of these steady-state trajectories, that is, whether perturbations or deviations in the state from the steady-state trajectory cause the system to converge towards the steady-state trajectory or diverge away from it. Two questions arise with regards to stability and actuator phasing. The first concerns the effects of actuator phasing on the stability of the system. The second is whether controlling actuator phasing can be used to stabilize the system, thus providing an alternative to Raibert's controller for stabilizing a monopod.

The stability of these steady-state trajectories depends on the method of control. The same trajectory will have different stability properties if, for example, the leg landing angle or t_{on} is controlled open- or closed-loop. In our study, we consider the situation in which the runner is controlled such that the leg landing angle and t_{on} are constant. In a real implementation, this would imply that during the airborne phase the leg is re-positioned at a predetermined angle for landing, and that when landing is sensed (e.g. by a binary contact switch), a timer that counts to t_{on} before activating thrust is reset to zero. To compute stability, we look at the multi-variable derivative, or

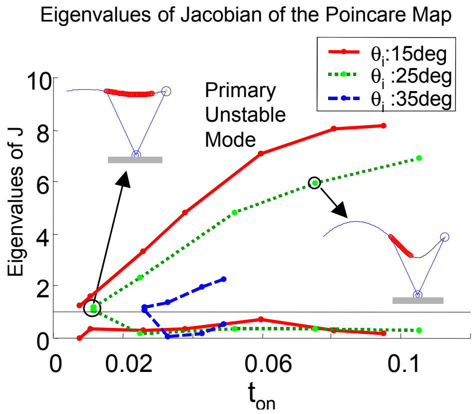

Figure 5. Eigenvalues of the Jacobian of the Poincare Map.

Jacobian, of the Poincare Map introduced in Equation 6:

$$J = \frac{\partial M}{\partial(\theta_{V(n)}, |V|_{(n)})} = \begin{bmatrix} \frac{\partial\theta_{V(n+1)}}{\partial\theta_{V(n)}} & \frac{\partial\theta_{V(n+1)}}{\partial|V|_{(n)}} \\ \frac{\partial|V|_{(n+1)}}{\partial\theta_{V(n)}} & \frac{\partial|V|_{(n+1)}}{\partial|V|_{(n)}} \end{bmatrix} \quad (7)$$

Evaluated at a particular steady-state trajectory, this Jacobian maps disturbances in the direction and magnitude of the landing velocity from one cycle to the next:

$$\begin{bmatrix} \Delta\theta_{V(n+1)} \\ \Delta|V|_{(n+1)} \end{bmatrix} = J \begin{bmatrix} \Delta\theta_{V(n)} \\ \Delta|V|_{(n)} \end{bmatrix} \quad (8)$$

Local stability of the steady-state orbit is given by the magnitudes of the eigenvalues, λ_i, of this Jacobian [10]. The trajectory is said to be locally stable if all of the eigenvalues $|\lambda_i| \le 1$, asymptotically stable if $|\lambda_i| < 1$ and unstable if $|\lambda_i| > 1$ for at least one eigenvalue. This Jacobian is computed numerically through simulation. The first column of the Jacobian is found by introducing a known perturbation in the θ_V direction at landing, and measuring the resulting changes in θ_V and $|V|$ at the next cycle. The second column is found similarly with known perturbations in $|V|$. In this case, a range of positive and negative perturbations were used, and the resulting Jacobian elements were averaged.

Figure 5 shows the eigenvalues of the Jacobian for the steady-state trajectories found earlier. As shown, trajectories are unstable, largely due to one unstable mode. Examination of the elements of the eigenvector that corresponds to this unstable eigenvalue showed that this mode is in the direction of $\Delta\theta_V$. This unstable

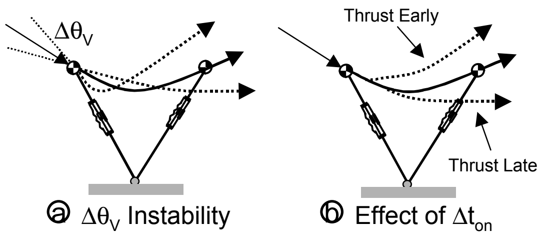

Figure 6. a) Unstable mode in the direction of the landing velocity. b) Effect of changing the time of thrust activation from its nominal value.

behavior is illustrated in Figure 6a, wherein small changes in the direction of the landing velocity result in large deviations in the take-off velocity, and subsequent landing velocity. Also of interest is the indication that “skittering” trajectories are less unstable, as shown by the decrease in the magnitude of the eigenvalue for low values of t_{on}. Thus, skittering trajectories appear to have an advantage in both forward velocity and stability.

In essence, the “neutral-point” foot-placement algorithm implemented by Raibert [1] in his hoppers served to stabilize the unstable mode in the $\Delta\theta_V$ direction by altering the leg landing angle appropriately. Although this approach works remarkably well, consideration of the previously ignored “knob” that varies the instant that thrust is activated leads one to ask whether this “knob” can be used to stabilize a monopod with a fixed leg landing angle. Such a method for stabilization would provide an alternative to Raibert’s foot placement controller. In simulation, changes in t_{on} can have a significant effect on the stance trajectory, as illustrated in Figure 6b. To formally show that changing the timing of thrust activation can stabilize the system, we write the following linearized discrete system:

$$\begin{bmatrix} \Delta\theta_{V(n+1)} \\ \Delta|V|_{(n+1)} \end{bmatrix} = J \begin{bmatrix} \Delta\theta_{V(n)} \\ \Delta|V|_{(n)} \end{bmatrix} + T\Delta t_{on(n)} \quad (9)$$

where $\Delta t_{on(n)}$ is assumed as the control input to the linearized system that maps disturbances from one cycle to the next. T is the vector representation of the linearized map between changes in t_{on} to changes in the direction and magnitude of the landing velocity at the next landing instant:

$$T = \begin{bmatrix} \frac{\partial\theta_{V(n+1)}}{\partial t_{on(n)}} \\ \frac{\partial|V|_{(n+1)}}{\partial t_{on(n)}} \end{bmatrix} \quad (10)$$

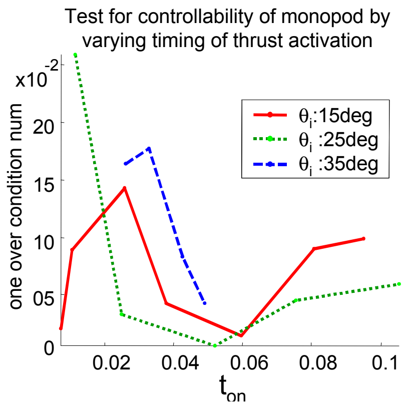

Figure 7. Inverse of the condition number of the controllability matrix for a monopod in which actuator phasing is used for the stabilization of forward motion.

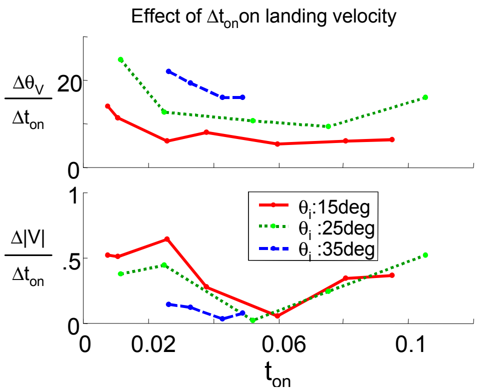

Figure 8. Quantitative effect of changes in t_{on} on the direction and magnitude of the landing velocity at the next cycle.

In the proposed control framework, the timing of thrust activation is varied from its nominal value in response to changes in the direction and magnitude from the nominal trajectory, according to a simple feedback law:

$$\Delta t_{on(n)} = \begin{bmatrix} k_1 & k_2 \end{bmatrix} \begin{bmatrix} \Delta\theta_{V(n)} \\ \Delta|V|_{(n)} \end{bmatrix} \qquad (11)$$

To show that such a feedback law for $\Delta t_{on(n)}$ can stabilize the system, we show that the discrete system in Equation 9 is controllable [12]. Controllability implies that the poles of the closed-loop system can be placed arbitrarily. A two-dimensional discrete system of the form of Equation 9 is controllable if the following matrix C is full rank:

$$C = \begin{bmatrix} T & JT \end{bmatrix} \qquad (12)$$

Using the matrices J found previously, and computing the vector T, the matrix C for the continuum of steady-state trajectories analyzed earlier was found. The vector T is computed by introducing known perturbations in t_{on} and observing the resulting changes in θ_V and $|V|$. The condition number of C, which is the ratio of the largest eigenvalue to the smallest eigenvalue, is used as an indicator of whether C is full rank. Its inverse is plotted in Figure 7 as a function of the value of t_{on} for each trajectory. A zero value for the inverse indicates that the matrix is singular, and that the system is not controllable.

As shown in the figure, the inverse is non-zero for small values of t_{on}. This implies that the system is controllable for the range of trajectories characterized as "skittering" running. This can be explained by looking at the values of the element of the vector T as a function of t_{on}. Shown in Figure 8, these values decrease for mid-values of t_{on}. These values of t_{on} correspond to trajectories in which thrust is activated near maximum compression of the leg. When thrust is activated near maximum compression, $\Delta t_{on(n)}$ loses "control authority," as velocities near maximum compression are minimal, and changes in t_{on} have a lesser effect on the trajectory.

This section has shown how stability can vary with actuator phasing, and how closed-loop control on the timing of actuation can stabilize a monopod with a fixed leg landing angle. The following section looks at the possible role of actuator phasing in adaptation in systems like the hexapedal robots we have developed, which do not require active feedback for stabilization.

5. Actuator Phasing in Adaptation

The Sprawl family of robots demonstrates that a well-designed mechanical system with appropriate placement of compliance and damping and leg configuration can locomote quickly and robustly without sensory feedback. However, a particular open-loop motor pattern or set of leg angles may not always result in optimal running given changes in terrain (e.g. slope) or loading conditions (e.g. carrying an object). For example, a stride period that is optimal for one ground slope may not be optimal for others. Thus, we are motivated to introduce adaptation, in which the parameters of the open-loop system are adjusted, or "tuned," to achieve optimal performance.

An adaptation framework that complements the design of the robots and takes advantage of its self-stabilizing properties is shown in Figure 9 (adapted from [4]). The passive properties of the system are relied upon for immediate disturbance rejection, while a slow feedback loop analyzes sensory information and adapts the open-loop parameters to optimize for changes in the environment or loading conditions. This significantly reduces sensor bandwidth requirements, and allows for sensor failures, in which case

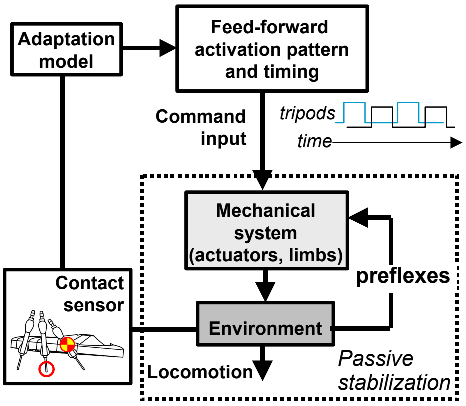

Figure 9. Adaptation framework that takes advantage of self-stabilizing passive properties. Adapted from [4].

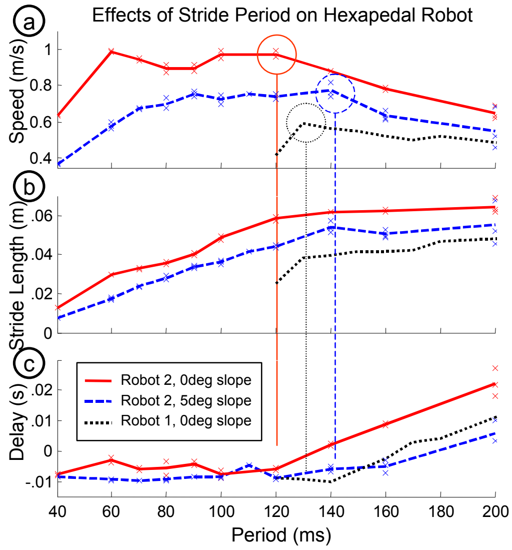

Figure 10. Experimental performance data of two versions of the hexapedal robots.

the system simply reverts to its nominal open-loop behavior.

Taking advantage of the relationships discussed in this paper between actuator phasing, work and performance, we can devise an adaptation scheme that further simplifies sensor requirements. As shown in Section 3, performance, in terms of maximizing stride length, is maximized when the actuator phasing is such that maximum work is being performed by the actuators. This is true in the simplified runner model for a range of leg landing angles. An adaptation strategy that focuses on adjusting the phasing of the actuators such that the work they perform is maximized would hypothetically maximize stride length despite changes in the leg configuration, or even changes in terrain or payload. Furthermore, the relationship established in Section 2 between the work performed by the actuators and the timing of thrust activation and deactivation provides a way to monitor work without complex sensors. As established for short thrust durations, work is maximized when thrust deactivation occurs near the time that the leg reaches maximum extension and the foot leaves the ground. Thus, it becomes possible to monitor performance through the amount of work done by the actuators as measured by the relative timing between actuator deactivation and loss of contact. This relative timing can be measured by a simple binary contact switch at the foot.

Performance tests on the hexapedal robots confirm this correlation between thrust timing and performance. Figure 10 shows the forward speed, stride length and time delay between thrust deactivation and take-off in the middle leg for two configurations of the Sprawl robots. These quantities are plotted as a function of the stride period of the open-loop motor pattern. Robot 2 differs from Robot 1 in the use of pneumatic pistons with less damping and higher flow rates. Also shown is the data for Robot 2 on a 5 degree slope. As shown, decreasing the stride period maximizes forward speed, up to the point where actuator bandwidth starts to limit performance. Stride length is constant for long periods, and decreases as period is decreased. An appropriate target for adaptation is the shortest period possible in which stride length is at a maximum, shown circled in the plots. Shorter stride periods from this value decrease stride length, as the net work performed by the actuators is decreased, while longer periods have decreased speed. This period is shown to correspond in Figure 10c with the period in which the graph of the delay changes slope and begins to increase. This change in slope marks the period in which thrust deactivation starts to occur near take-off. This correspondence is apparent in all three cases. Thus, though the dynamics of the robot are complex, it appears that measuring the time delay between thrust deactivation and take-off can give a first-order indication of the period in which optimal stride length is achieved.

This correlation was used as the basis for an adaptation law that adjusts the stride period in order to place deactivation near take-off such that maximum work is performed. This adaptation law looks at the delay between deactivation and take-off at each stride, measured by a simple binary contact switch in one of the robot's middle legs, and makes adjustments on the stride period on a stride-to-stride basis. Details on the prototype adaptation can be found in [11]. Figure 11 shows sample results for multiple runs in which the robot was started at suboptimal stride periods, and allowed to self-adapt over time. The top plot shows the speed of the robot as it adapts, and shows how speed reaches a maximum. The bottom plot shows the stride period as it converges to the optimal value.

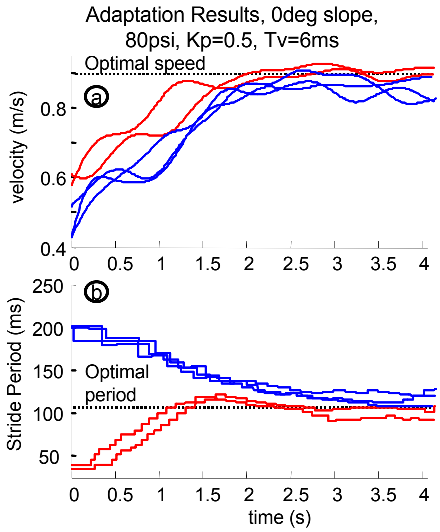

Figure 11. Sample results of the adaptation law based on the relationship between performance, work, and actuator phasing.

More results and a discussion on some of the limitations of this approach can be found in [11].

6. Conclusions

This paper has provided an examination on the role of actuator phasing in running. A relationship between actuator activation and deactivation in a simplified model of running was established. It was found that the work performed by the actuator is not necessarily maximized when thrust activation occurs at the leg's maximum compression. This work was then correlated to performance in steady-state trajectories of the model. Results show that stride length is maximized in trajectories in which the work performed by the actuators is maximized. On the other hand, forward speed is maximized in trajectories in which thrust is initiated shortly after landing. Both these results suggest that hoppers that activate thrust at the leg's maximum compression, as originated by Raibert, may be operating sub-optimally in terms of both efficiency and speed.

These relationships between actuator timing and the motion of the system were used in two situations for control and adaptation. First, it was shown that actuator timing can be used to stabilize the monopod model, which was found to be unstable under open-loop control. This use of thrust timing for stabilization provides an alternative to Raibert's "neutral-point" foot placement controller. Second, the correlation between actuator phasing and performance was used for adaptation in a hexapedal robot that is stable under open-loop control. Monitoring the phasing between actuator deactivation and take-off allowed an adaptation algorithm to adjust the stride period of the open-loop motor pattern to place these events such that maximum work and optimal performance are achieved.

These results lead to the general idea that subtle changes in the timing of actuation can have a significant impact on dynamic movements such as running, and can be utilized for control and adaptation. Changes in the timing of actuation for control can be relatively inexpensive to implement in comparison to an added actuated degree of freedom. Correlating quantities difficult to measure in dynamic tasks (e.g. efficiency) to actuator phasing as measured by simple binary events can significantly reduce the sensory requirements for control and adaptation.

5. Acknowledgments

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