On the use of Hybrid Control for Legged Locomotion

S.V. Shastri, ne S.T. Venkataraman
SRI International
333 Ravenswood Avenue, Menlo Park, CA 94025

***e-mail:* venkat@erg.sri.com**

Abstract

In this paper, we develop a hybrid control approach for legged locomotion. We motivate the development of the control architecture using the results of a series of walking, running and obstacle climbing experiments conducted using a six legged robot called HEX. Our initial simulation results indicate the potential stability of the control approach, and our future analytical work should provide the formal proof of these results.

I. Introduction

It is well known that legged locomotion involves the use of prototypical movements wherein the phase, frequency and amplitude of individual leg motions are related to one another in specific ways. In the literature, such movements are referred to as gaits. It is also well known that the neural circuitry in most biological systems contain programs for multiple gaits. Typically, animals appear to select and switch between gaits depending on a range of factors such as body speed, unknown terrain geometry and variations in terrain physics. From a phenomenological point of view, this may be viewed as an example of a control system that attempts to maximize system performance and robustness in the presence of large disturbances (and possibly model uncertainties) by possibly switching between control laws. As such therefore, legged locomotion could well serve as a problem area for the study of hybrid control. This paper may be considered as a first step in our formal study of the use of hybrid control techniques for legged locomotion. It may be viewed as a logical next step after our gait modeling work [Shastri 1997].

We restrict our attention to hexapedal locomotion in this paper. The paper is divided into three parts. In the first, we describe open loop gait control experiments performed using a hexaped robot called HEX (Section II). The second part utilizes the experimental results and develops a hybrid control architecture for legged locomotion (Section IV). The hybrid control problem considered as a result is unique in that it considers switching between reference models in a model reference control architecture. The third part describes ongoing analytical work in the use of hybrid control for legged locomotion.

II. Experimental Results

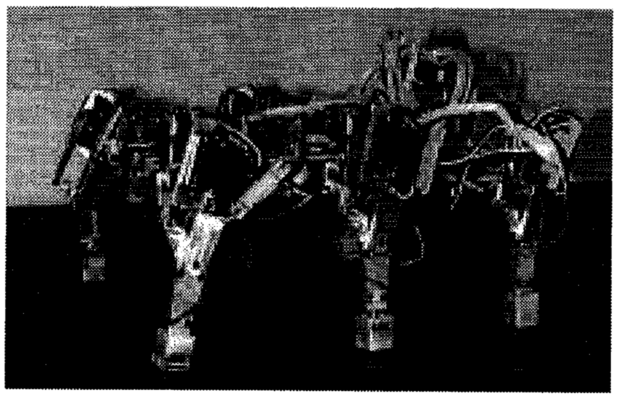

Figure 1: HEX, The Legged Robot

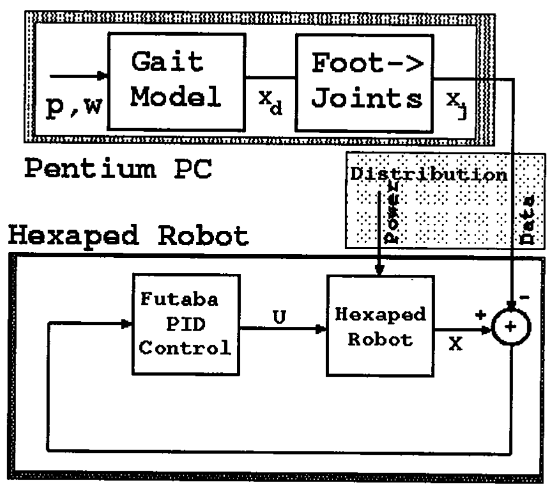

Figure 2: Implementation Setup

Table 1: Walking, Running and Climbing Experimental Results

Gait	Terrain	Speed	% Success
Both	Level	Range	100
Both	≥ 1" Single Step	Fixed	0
Both	< 1" Single Step	Fixed	100
Tripod	< 1" Double Step	Fixed	25
Wilson	< 1" Double Step	Fixed	40
Tripod	< 1" Triple Step	Fixed	5
Wilson	< 1" Triple Step	Fixed	20

As part of this ongoing effort, a legged robot has been built for experimental work (Figure 1). It has six legs, each with four-degrees-of-freedom. Three of these are at the hip, and one at the knee. Two of the three degrees-of-freedom at the hip is actuated using a differential gear arrangement. All the joints are driven by Futaba servo motors, which are commanded with position commands. Each servo has an internal PID position control loop in hardware at a sample a rate of about 2.5 KHz. There is a contact sensor mounted on each foot of the robot. The robot is about 50 cms long, 30 cms wide and 15 cms tall. The robot is controlled by a data acquisition card mounted on the backplane of a PC. All control programs are developed in C Programming Language, cross compiled to the native assembly language of the processor on the data acquisition card and used for commanding the Futaba servos.

Results from the numerous runs on level ground as well as climbing over obstacles may be summarized as shown in Table 1. These experiments consist of walking and runing experiments using both the Wilson gait and the tripod gait, and climbing over unknown obstacles. The implementation architecture utilized for the purpose (described in Figure 2) generates nominal leg motions using the gait models suggested in our earlier work, and performs PID type servo control at the joints. Tests on level ground were performed using a tripod gait over a range of body speeds, starting from about 1 body length *per* minute to about 30 body lengths *per* minute. Tests with the Wilson gait were performed between 1 and 8 body lengths *per* minute. Obstacles were configured in the form of a single, double or triple step and a fixed climbing speed of about 4 body lengths *per* minute was utilized. All the tests on level ground were completely successful, implying that the locomotion was stable, without significant slippage between the legs and the ground (despite the absence of any foot force sensors). For any of the step configurations, if the step height was ≥ 1", the legs could not clear past the obstacle. This is indicated by the *0%* success in Table 1. For single step obstacles when the step height was < 1", the robot was always successful, independent of the *approach angle*. For the two and three step configurations, the success rate depended very much on the approach angle. When the robot tried to climb the obstacle with $\theta = 0$, the motors saturated more often (input saturation) than otherwise. As a result, success rates were quite low (as indicated in Table 1). When the approach angles were very large ($\theta > 50^\circ$), input saturation appeared to lower the success rate as well. While a uniform degradation in performance was seen as the obstacles got worse, experiments with the Wilson gait appeared to have better results than with tripod gait. Note that in all of the experiments the robot was able to maintain stability (e.g., did not fall or flip over), but this may be largely due to sufficient number of legs supporting the body at all times. Similar experiments with biped or quadruped robots cannot be expected to yield such stability properties.

III. Discussion

In all of the climbing experiments, input saturation occurs due to, (i) an increase in the magnitude of control signals required for climbing, and (ii) a decrease in the coefficient of friction between legs and the ground due to change in terrain in geometry. The former is related to the fact that climbing requires overcoming larger potential energy, and may be why there is a slight improvement in performance when employing the Wilson gait (greater number of legs on the ground in general implies larger total body forces for a given leg-ground force value). The decrease in friction coefficient results from premature contact between ground and the heel of a foot. For example, as shown in Figure 3, a step obstacle results in reduction of the friction area from that of the footprint, to a line that is as long as the width of the foot. Such contact effects occur due to the absence of detailed knowledge about terrain geometry (and the resulting inability to shape gait trajectories to *fit* the terrain), combined with our assumption about treating changes in terrain geometry as an external disturbance. One way to overcome this problem is to place force sensors on the feet of the robot, and treat gait trajectories as compliant motion trajectories. An alternate way might be to integrate inclinometers and rate gyros on to the body of the robot, and use this information for modifying gait trajectories. A third, and perhaps the most computationally atractive method is to drive the legs using compliant actuators (e.g., artificial muscles), and use their passive compliance to re-orient the legs and improve contact friction. The last approach is evidenced in many biological systems, and is argued as the basis for passive stabilization of the body as well. We are currently investigating the use of Electrostrictive Polymer Artificial Muscles (EPAMs) for this purpose.

It is also clear from discussions in the previous section that the Wilson gait tends to outperform the tripod gait, and as a result should be the preferred choice in various insects. Evidence from biology, on the other hand, appears to indicate the use of Wilson gait only in stick insects, and certain arthropods during very slow walking. In this paper, we argue that the reason for this might lie in the computational complexity involved in implementing the two gaits. As far as tripod gait is concerned, with a duty factor of *0.5*, the frequency of oscillation is roughly that of the forcing signal. In the case of Wilson gait, however, the need to maintain a duty factor of *1/6* results in higher harmonics. The power spectra of a typical Wilson-like response when forced with a *1Hz* harmonic signal was shown to be spread out between *0Hz* and *22Hz* (with most of power residing in frequencies under *10Hz*) in our earlier work. As a result, gait signals would have to be generated at atleast about *45x* the leg movement frequency desired. This is likely to pose a tremendous computational overhead, and as a result is not likely to be the preferred gait at higher speeds. As a result, depending on the operating conditions, the preferred gait might vary between tripod and the Wilson as a result of athe tradeoff by , and a locomotion architecture that has the ability to switch between gait models and tune their parameters on line would be vital to achieving uniform system performance over a range of speeds and terrain conditions. Our work in hybrid control is motivated precisely by this observation. We have already developed a hybrid control architecture for locomotion, and have started to test the potential of hybrid control techniques for legged robots. In the following sections, we report the state of this work in progress.

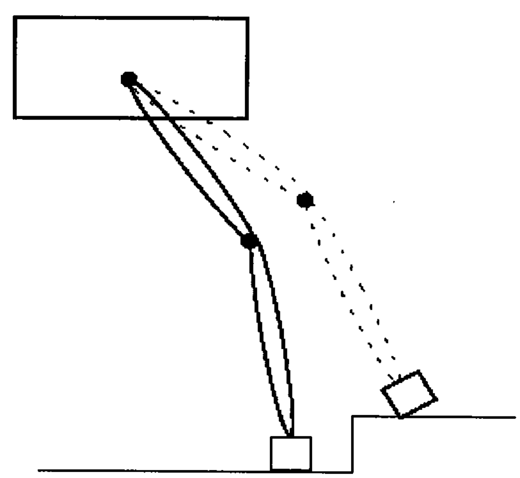

Figure 3: Premature Leg-Ground Contact

IV. A Hybrid Control Architecture for Legged Locomotion

Discussions in the preceeding section demonstrate that legged locomotion involves the use of multiple gaits. It is also reasonable to assume that these gaits would need to *tuned* on line to match the geometric and physical characteristics of terrain. In the experiments conducted thus far, we have generated the desired motion of various legs using gait models, discretized them into position setpoints and performed PID control of actuators for realizing the desired motion on various legs. Despite the simplicity of such an approach, its applicability to situations where gait models may be switched and tuned on line may be quite limited. In this section, we discuss this issue in some detail, and present a control architecture for legged locomotion that has the ability to accomodate gait switching and gait tuning.

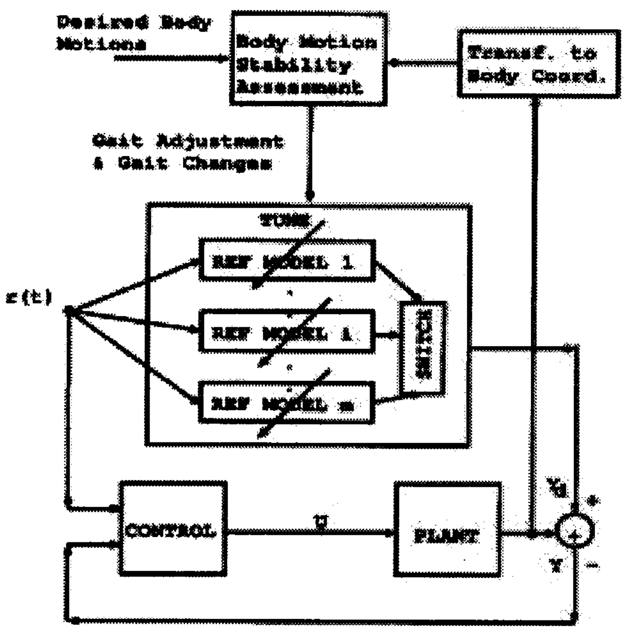

Figure 4: A Control Architecture for Legged Locomotion

In systems theory, control objectives are stated typically using certain types of error functions. Some of these relate to how closely various states (outputs) of a dynamical system may be maintained around prescribed quantities. Specification of the latter could occur in one of three distinct ways: reference setpoints, reference trajectories and reference models. The initial experiments has considered setpoint control due to its inherent simplicity in design. On the other hand, it is well known that this approach may be too limiting a framework for specifying complex robot behaviors. Reference trajectory following schemes allow specification of complicated maneuvers and is in fact most commonly used in robotics. Modification of gait trajectories on line might result in a change in the order of reference trajectories and must be dealt with in the information specified of a controller. Such an eventuality may be accounted for by considering the highest order of the trajectories generated by all gait models (with some tuning schemes). A reference model approach would also have the ability to capture complex robot behaviors. In addition, it would permit the investigation of control design for classes of tuning laws, and classes of gait model switching laws. In view of this, we propose the use of a model reference control approach for locomotion and suggest the architecture in Figure 4 for the control of locomotion. In such a setting, gait control would involve the design of a model reference controller. In the event that the plant has model uncertainties, gait control would involve the design of model reference adaptive control with appropriate adaptation laws. Gait tuning would be implemented through changes made to the parameters of gait models, and gait switching would occur as a result of switching between reference models on line. Further, realization of a gait would involve the demonstration of the existence of a model reference controller. Stable gait tuning laws for which controller exist would be permissible and rules that guarantee stability of the overall system during transitions would be considered the allowable switching between gaits.

IV.1. Initial Simulation Results

Assuming that the use of compliant actuators passively stabilizes the contact between legs and the ground, the problem of controlling leg motions may be represented in a manner similar to multifingered hand control problem described in [Li and Sastry 1989]. As far as leg movements are concerned, the plant model for each leg is given by:

$$\dot{x} = f(x) + g(x)u + J(x)F$$

where $x \in R^n$ is the state of the system (joint positions and velocities), $u \in R^m$ is the joint torque vector, $F \in R^p$ is the foot to ground forces, and f and g are smooth functions. For HEX, $n = 8$, $m = 4$, and $p = 3$. It is quite well known that the dynamic model described above may be re-qritten in the form

$$\dot{x} = p_1 f(x) + p_2 g(x) u + J(x) F$$

where p_1 and p_2 are vectors of fixed value parameters that are related to link masses and link lengths. To study the performance of the multiple model reference control problem, we simplify the model described above with the assumption that the legs are in free motion (i.e., $F = 0$). Consider the simplified plant model with scalar parameters a and b. Let the true values of these parameters (which are unknown) be $p_1 = 0.25$ and $p_2 = 1.0$. Let the control objectives be to track the reference trajectory x_d generated by cyclically switching between two reference models R_1 and R_2.

In the actual simulation, both reference models are forced van der Pol oscillators with different parameters (and hence different limit cycles). Control design and control parameter update laws were derived for the case when all of the states were fully accessible. Control designs were performed using the design principles provided in [Narendra 1989] and [Seto 1994], [Kanellakopoulos 1991]. From Figure 5, it is evident that the controller is able to quickly adapt as the reference models switch. There is, however, some transient error every time a switch occurs. Figure 4(a) shows the model following performance, while Figure 4(b) shows the tracking errors. Figures 4(c) and 4(d) show the parameter learning performance.

V. Ongoing Systems Theory Research

We are currently deriving formally results related to proof of stability for systems that are placed under multiple model reference control. Our analytical work considers linear systems first, and then extend results to the class of nonlinear systems with analytic vector fields. We will present these results to date, and motivate the conditions under which the overall dynamical system remains stable during switching. In addition, the applicability of switching rules such as cyclic switching and random switching will be explored for locomotion over rugged terrain.

VI. Acknowledgements

The work described in this paper is supported in part through the NSF Grant IRI-9530915 and through an ONR Grant (SRI project 1686). The author would like to thank John Koo for his help in the controls analysis work.

VII. References

[Kanellakopoulos 1991] Kanellakopoulos, I., Kokotovic, P.V., Morse, A.S., ``Systematic Design of Adaptive Controllers for Feedback Linearizable Systems", *IEEE Transaction on Automatic Control*, vol. 36, 1991, pp. 1241-1253.

[Li and Sastry 1989] Li, X., Sastry, S.S., ``A Unified Approach for the Control of Multifingered Robot Hands," *Contemporary Mathematics*, 97:217-239, 1989.

[Narendra 1989] [Narendra 1989] Narendra, K.S., Annaswamy, A.M., *Stable Adaptive Systems*,Prentice Hall, 1989.

[Seto 1994] Seto, D., Annaswamy, A., Baillieul, J., "Adaptive control of nonlinear systems with triangular structure," *IEEE Transactions of Automatic Control*, 1994.

[Shastri 1997] Shastri, S.V., "A biologically consistent model of legged locomotion gaits," *Biological Cybernetics*, 1997.

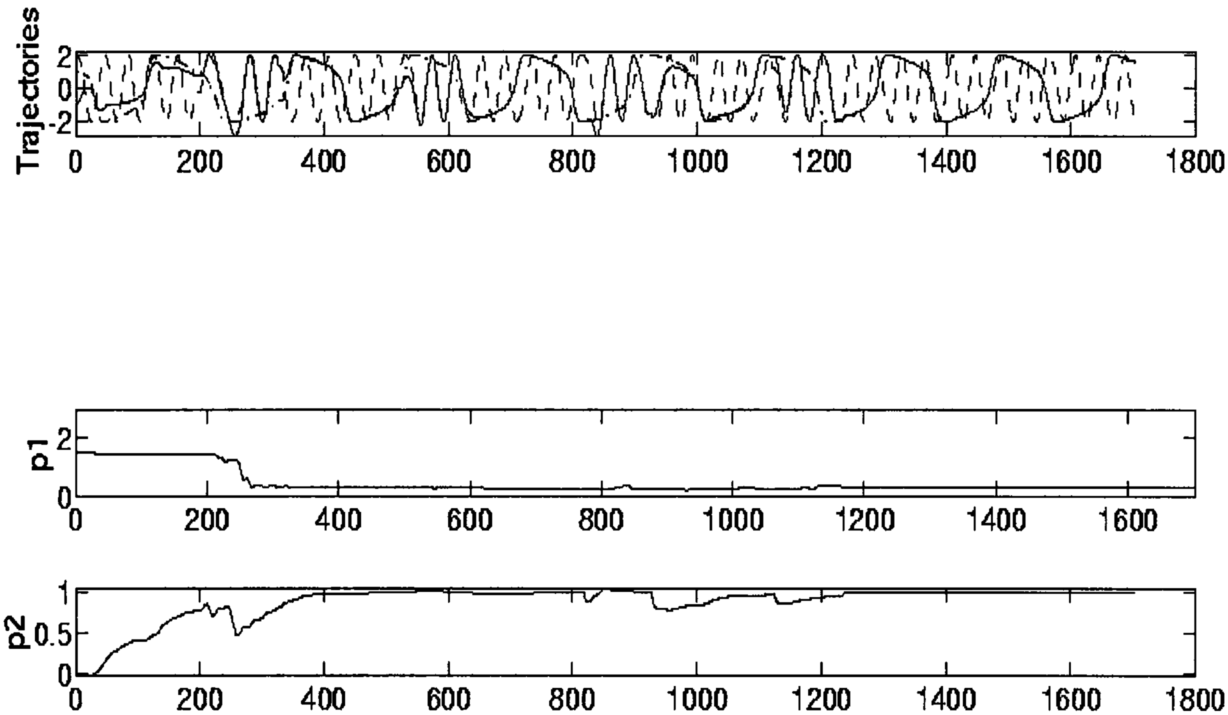

Figure 5: Adaptive Multiple Model Reference Control Simulations