Adjusting Step Length for Rough Terrain Locomotion

Jessica K. Hodgins and Marc H. Raibert, *Member, IEEE*

***Abstract*—To travel on rough terrain, a legged system must adjust the length of its steps so that the feet land on the available footholds. This paper explores the task of controlling step length in the context of a dynamic biped robot that actively balances itself as it runs. We explored three methods for controlling step length, each of which adjusted a different parameter of the running cycle. The adjusted parameters were forward running speed, running height, and duration of ground contact. All three control methods were successful in manipulating step length in laboratory experiments, but the method that adjusted forward speed provided the widest range of step lengths (0.1 to 1.1 m) with accurate control of step length (average absolute error of 0.07 m). The three methods for controlling step length manipulated the dynamics of the system so the feet could be placed on the available footholds without disturbing the system's balance. An alternative approach was to ignore balance for a single step, placing the foot directly on the desired foothold, and recovering balance later. This approach generally resulted in very precise foot placements for a single target but could not be used to control many steps in a row. In laboratory demonstrations a biped running machine used these methods for adjusting step length to place its feet on targets, leap over obstacles, and run up and down a short flight of stairs.**

I. Introduction

Dynamic legged systems should be able to traverse more difficult terrain than static systems of comparable size and reach. Dynamic legged systems that use a ballistic flight phase do not need a continuous path of support, a broad base of support, nor closely spaced footholds. They can leap over regions of terrain that offer no good footholds at all. Generally, a dynamic legged system can use its kinetic energy to bridge from one foothold to another. Some day dynamic legged systems may travel on terrain that is too rough for wheeled and tracked vehicles.

These potential advantages of dynamic legged systems are obtained at the expense of more complicated control for placing the feet on desired footholds. Foot placement is straightforward in statically stable systems, once a reachable foothold has been chosen. Inverse kinematics and joint servos can be used to position each foot on the foothold. In dynamic legged systems, however, the act of positioning the feet with respect to available footholds interacts with the stability and general behavior of the system. Each placement of a foot on the ground causes the body to accelerate and influences the forward speed and direction of travel. The algorithm responsible for placing the feet must manipulate the dynamic parameters of the system to simultaneously balance the machine and keep it moving as desired.

Manuscript received September 1, 1989; revised October 22, 1990. This work was supported by the Information Sciences Technology Office of the Defense Advanced Research Projects Agency under Contract MDA903-85-K-0179 and by the System Development Foundation. A portion of this work was presented at the IEEE International Conference on Robotics and Automation, Philadelphia, PA, 1988.

J. K. Hodgins was with the Artificial Intelligence Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139. She is now with the IBM Thomas J. Watson Research Center, Yorktown Heights, NY 10598.

M. H. Raibert is with the Artificial Intelligence Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139.

IEEE Log Number 9142997.

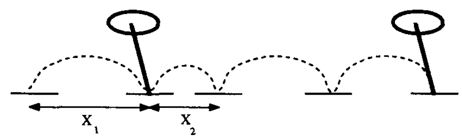

Fig. 1. One-dimensional rough terrain consists of a series of footholds with uneven spacing in the direction of running. The footholds lie on a line in front of the machine and the legged system is constrained to move fore and aft, up and down, and to rotate about the pitch axis. Three-dimensional rough terrain would include vertical and lateral variations in the spacing of footholds.

The problem of controlling a dynamic legged system to travel on rough terrain includes many subproblems, including sensing the terrain, planning a path, selecting a foothold, and adjusting step length. This paper concentrates on the last of these problems, the need to adjust the length of each step so the feet are placed on chosen footholds. To study the placement of feet on footholds, we considered a special case of rough terrain locomotion in which the footholds are unevenly spaced on a straight line in the horizontal plane (Fig. 1).

We used a planar biped running machine to evaluate three methods for controlling step length. One method adjusted the forward running speed of the system while keeping the duration of the stance and flight phases constant. The second method adjusted the duration of the flight phase while holding constant the forward running speed and the duration of the stance phase. The third method for controlling step length adjusted the duration of the stance phase while the forward running speed and the duration of the flight phase were held constant. The various adjustments were made by varying the foot position, leg thrust, and leg stiffness on each step. The experiments showed that all three methods were able to provide changes in the step length while maintaining balance, but the forward speed method gave the widest range of adjustments with good accuracy.

One might ask what would happen if the control system temporarily ignored the need for balance and placed the foot exactly on the chosen foothold. We call this approach "direct placement." It could be expected to place the foot precisely

1042-296X/91/0600-0289$01.00

on target footholds, but at the expense of stability whenever there was a substantial discrepancy between the locations of the target foothold and the foothold that would have provided perfect balance. The system might recover its balance on subsequent steps if the discrepancy were small, but the system might tip over entirely if the discrepancy were large. Direct placement generally provided the highest accuracy when used to place the foot during a single step, but it could not control several steps in succession.

In the next section of the paper, we review previous work on rough terrain locomotion. Then we describe the planar biped machine used for the experiments in controlling step length and the details of the control methods studied. After data from the experiments are presented, we close with demonstrations of placing a foot on a target, jumping over obstacles, and climbing stairs.

II. Background

In this section we summarize previous studies of legged locomotion on rough terrain. First we discuss human locomotion studies and then robot locomotion.

Lee *et al.* [8] studied skilled human long jumpers, who must place their feet near the front edge of the takeoff board if they are to maximize their jump. A series of adjustments in step length permitted the jumpers to arrive at the takeoff board with their toes very near the leading edge. They concluded that subjects manipulated the vertical impulse delivered to the ground by the legs to adjust step length. Vertical impulse, the integral of vertical force exerted on the ground during the stance phase, determines the duration of the flight phase, and, assuming constant running speed, it also determines the length of each step. The use of vertical impulse to control step length is quite similar to the flight duration method for controlling step length we report below.

Warren *et al.* [24] studied how runners adjust step length when required to place their feet on randomly positioned footholds on a treadmill. They were primarily interested in the use of vision for placing the feet on visible targets. They too concluded that their subjects used vertical impulse to control step length, with nearly constant forward speed.

Patla *et al.* [21] explored the question of how step length is adjusted by humans running on flat, level terrain. In their experiments, runners were required to adjust the length of one step to be short, normal, or long, depending on a signal from the experimenter. Both the length of the adjusted step and the timing of the signal were varied. The stance period just prior to the adjustment occurred when the foot was on a force platform, so the data included ground force information as well as ground contact durations. The experimenters were able to determine which parameters were adjusted and how the choice of parameters was affected by the timing of the signal. The results indicate that both horizontal and vertical impulse were adjusted to control step length and that the timing of the signal for adjustment affected the parameters used to perform the adjustment. For example, when the cue occurred late in the step, the adjustment was made during the flight phase.

Patla's conclusion that both horizontal and vertical impulse are used to control step length is at odds with Warren's conclusion that adjustments in vertical impulse are the primary technique for controlling step length. This discrepancy may result from different experimental designs: the subjects in Warren's experiment ran on a treadmill while Patla's subjects ran on the ground. The treadmill may have artificially constrained the runner's forward speed to be constant, whereas the overground runners could vary their forward speed freely.

Research in robotic legged locomotion on rough terrain has focused on the statically stable case in which the legged system always has at least three feet on the ground and moves forward slowly. Simulation work concentrated on the problem of building a terrain map from sensor information so that footholds could be chosen that would allow the machine to proceed along the chosen path. Experimental work included machines controlled by humans and algorithms that allowed machines to walk over unknown terrain, evaluate footholds, and, most recently, walk outdoors on several different kinds of natural terrain.

For statically stable locomotion, the difficulty is not in placing the feet on footholds, but in deciding which locations on the terrain provide suitable footholds. A suitable foothold is one that allows the legged system to maintain balance and continue walking. Researchers have addressed this problem by beginning with a desired motion trace for the body and then using heuristic algorithms to select reachable footholds along the motion trace. For instance, Okhotsimski and Platonov [18], [19] simulated a hexapod walking on three-dimensional poles and holes terrain. Information from a simulated range finder was used to find feasible footholds given knowledge about the machine's physical limitations. The simulated machine walked using the sequence of support polygons found by the foothold selection algorithms, with the additional constraint that the maximum force for any leg should be minimized and that the reaction force should be kept as close to the axis of the friction cone as possible.

McGhee and Iswandhi [15] also worked on the problem of choosing appropriate footholds for six-legged walking, given a desired motion trace for the body and a model of the terrain. They proposed an algorithm for finding a sequence of acceptable footholds: legs closest to their kinematic limits in the direction of motion of the body were lifted and legs with the largest kinematic range in the direction of motion were placed first. These heuristics extended each support state forward and increased the probability that it would overlap with the next support state. Adaptability and avoidance of deadlock were emphasized over stability by maximizing the number of legs in the air. Computer simulation indicated that this approach generally found a sequence of appropriate footholds when the motion trace contained a large number of possible sequences.

Hirose [3] developed hierarchical algorithms to control the terrain-adaptive gait of a statically stable quadruped, given a desired motion trace for the body. One level provided gait control, so that the machine tended to converge to a crawl gait. The lowest level provided basic motion regulation, including such functions as controlling the pitch and height of the body and preventing collisions between the legs. Hirose demonstrated the feasiblity of these algorithms through computer simulations. The simulated quadruped walked across terrain with holes, crossed a river, and made local modifications to the motion trace to avoid a large hole.

The quadruped transporter built by Ralph Mosher and his colleagues at General Electric walked on rough terrain with a human providing control and sensing [9], [10], [16]. A human drove the machine by making crawling motions with his arms and legs. A hydraulic force-reflecting master–slave servo caused the four legs of the vehicle to follow the motions of the operator and provided force information from the legs of the vehicle back to the arms and legs of the operator. Despite the intense concentration required to drive the machine, Mosher was able to make it amble along at about 5 mi/h, climb a stack of railroad ties, and walk through an orange grove. These experiments showed that a legged machine can move effectively on rough terrain, provided it has excellent sensing and control systems, such as those provided by a human.

Hirose [3] built a quadruped that used a set of reflexes to walk on rough terrain. One reflex pulled the foot back and lifted it, if a touch sensor on the foot indicated that it had bumped into an obstacle as the foot moved forward. Another reflex caused support legs to push downward if a load cell in the foot indicated that it was not bearing an adequate vertical load. A third reflex caused the relative altitude of the feet to be adjusted so the body remained level, as indicated by an oil-damped pendulum. Hirose's quadruped used these reflexes to climb up and down steps without a model of the terrain.

Okhotsimski and his co-workers built a six-legged walking machine that could climb up onto a small ledge [1], [2], [17]. The machine was 0.7 m long and weighed 10 kg. The legs were powered by electric motors. Pitch and roll information was provided by a vertical gyroscope. The machine climbed by raising its body and then placing each foot up on the ledge. Care was taken to keep the body level during climbing.

McGhee's group at The Ohio State University (OSU) built a hexapod walking machine that used human input for foothold selection [13], [14], [20]. Like most legged vehicles, the OSU hexapod used human input to specify direction and speed of travel for walking on smooth terrain. In addition, it could position its feet on footholds that the human operator indicated by pointing with a laser. The machine used stereo cameras to locate the laser spot in three dimensions, evaluated the quality of the spot location as a foothold based on leg kinematic limits and vehicle stability, and placed a front foot on the foothold if it was acceptable. The two pairs of rear legs reused these same footholds, resulting in a follow-the-leader gait.

Waldron and McGhee [23] built a second hexapod at OSU called the Adaptive Suspension Vehicle. This vehicle was much larger than the first—5.2 m long, 2.4 m wide, 3.0 m high—and weighed 2700 kg. An operator rode on board to provide general speed and direction inputs, while leg coordination and foothold selection were provided by control computers. A range sensor provided terrain depth information for the 10 m of terrain in front of the vehicle. This machine was able to walk up and down grassy slopes, through a muddy cornfield, and over railroad ties.

III. Experimental Apparatus

To study the control of step length, we used a planar two-legged running machine for experiments. Figs. 2 and 3 illustrate the design of the machine. It has two telescoping legs connected to the body by pivot joints that form hips. Each hip has a hydraulic actuator that positions the leg fore and aft. An actuator within each leg changes the leg length, while an air spring makes the leg springy in the axial direction. The leg actuator and spring act in series. The biped is constrained mechanically to move fore and aft (x), up and down (z), and to rotate about the pitch axis of the body (ϕ). Fig. 4 shows the kinematics of the biped.

In a typical experiment, the planar biped travels around a circle with a running gait that uses one leg for support at a time. Each support phase is an elastic rebound during which the mass of the running machine bounces off the spring in the leg. Between each pair of stance phases is a ballistic flight phase, during which no feet touch the ground and linear and angular momentum are conserved. Every 6 ms the control computer collects data from the sensors, executes the control algorithms, sends outputs to the actuators, and records data for later analysis. The control system receives setpoints for the desired forward speed, hopping height, and stiffness of the leg springs from a control panel operated by a human driver or from a predetermined sequence of setpoints stored in the control program.

To develop the control algorithms for adjusting step length, we modified a set of control programs used previously to make the planar biped run. The approach in the previous algorithms was to decompose the control into three parts. One part regulated the amplitude of the machine's bouncing motion, another maintained the body in an upright posture, and the third controlled forward running speed. Experiments with these algorithms showed that they were adequate for running in place, running fast (13 mi/h), switching gaits between hopping and running, and performing simple gymnastic maneuvers [5]–[7]. These control algorithms worked by adjusting running speed, hopping height, and body posture, but they did not specify the length of the step nor the locations on the ground where the feet were to be placed. We developed algorithms for adjusting step length by extending these algorithms.

IV. Control of Step Length

The length of a step is the distance between two successive footholds, as illustrated in Fig. 5.[1] During steady-state running, the step length is the distance traveled during the stance phase plus the distance traveled during the flight phase

$$L_{\text{step}} = \dot{x}_s T_s + \dot{x}_f T_f \tag{1}$$

[1] In the biomechanics literature, "step length" refers to the distance traveled by the body while the foot is on the ground, but that is not the definition used in this paper.

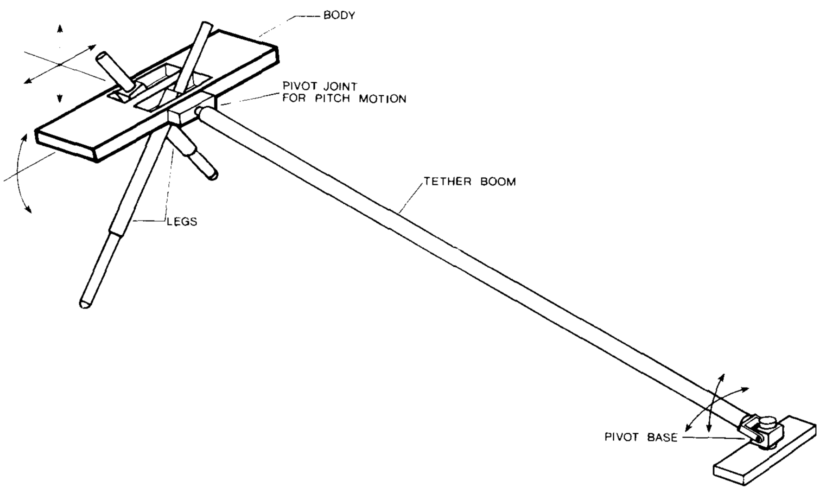

Fig. 2. Diagram of the planar, two-legged running machine used for experiments. The body is an aluminum frame on which are mounted hip actuators and computer interface electronics. Each hip has one low-friction hydraulic actuator that positions the leg fore and aft. An actuator within each leg changes its length, and an air spring makes the leg springy in the axial direction. Sensors measure the lengths of the legs, the positions and velocities of the hip actuators, pressures in the air springs, contact between the feet and the floor, and the pitch angle of the body. An umbilical cable connects the machine to hydraulic, pneumatic, and electrical power supplies and to the control computer, all of which are located nearby in the laboratory. The arrangement of body, legs, hips, and actuators provides a means to control the position of the feet with respect to the body, to generate an axial thrust with each leg, and to provide hip torques during running. A tether boom constrains the machine to move fore and aft, up and down, and to rotate about the pitch axis. The tether boom also provides a means of sensing body pitch angle and vertical and horizontal position in the room. The biped pivots freely with respect to the tether boom about the pitch axis.

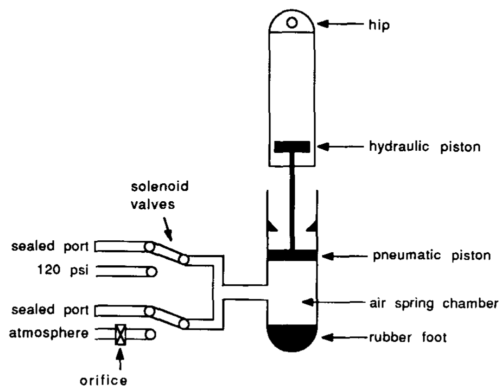

Fig. 3. Schematic of the leg used in the planar biped machine. A hydraulic actuator acts in series with a pneumatic spring. The hydraulic actuator drives the vertical bouncing motion of the machine and retracts the leg during flight. Two-way solenoid valves regulate the flow of air to the chambers of the spring and seal off the chambers during the stance phase. The foot is a rubber hemisphere with a 3-cm diameter. Sensors measure hydraulic actuator length, overall leg length, pressure in the pneumatic spring, and contact between the foot and the ground.

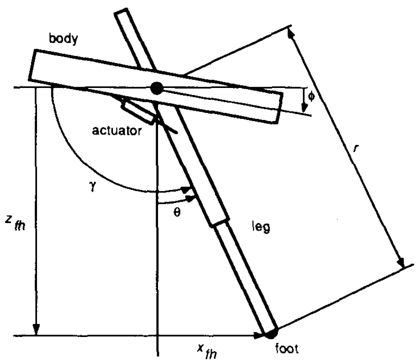

Fig. 4. Kinematics of planar two-legged running machine. The length of the leg is r, the angle between the leg and vertical is θ, the angle between the body and the leg is γ, and the pitch angle of the body is ϕ. $\theta = \gamma - \phi - 90$. Horizontal foot position relative to the hip x_{fh} is equal to $r \sin \theta$. The kinematics for the second leg are similar except that the hip actuator is attached to the other side of the body.

where $\dot{x}_s$ and $\dot{x}_f$ are the average forward running speeds during the stance and flight phases, and T_s and T_f are the duration of the stance and flight phases, respectively. The distance traveled by the body during a given period is the product of the duration of the period and the forward speed. Therefore, variations in the duration of the flight phase, in the duration of the stance phase, or in the forward running speed each can influence the step length. These observations suggest three methods for controlling step length while maintaining balanced running:

Forward Speed Method—For given durations of the stance and flight phases, forward running speed determines step length. The control system manipulates the forward running speed by positioning the foot to accelerate or decelerate the system on each step. The control system can position the foot to cause zero, positive, or negative net acceleration during the next stance phase, as shown in Fig. 6. The forward position of the foot at touchdown is specified by

$$x_{fh} = \frac{T_s \dot{x}_s}{2} + k_{\dot{x}}(\dot{x}_f - \dot{x}_d) \tag{2}$$

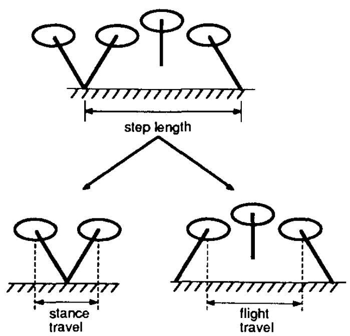

Fig. 5. Step length is the distance traveled during the stance phase plus the distance traveled during the flight phase. The length of a step can be modified by changing the forward speed, duration of the stance phase, or duration of the flight phase.

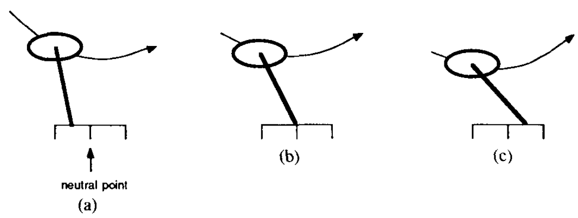

Fig. 6. Controlling forward speed. (b) When the foot is placed in front of the hip one-half the distance the body will travel while the foot is on the ground, the forward speed will remain unchanged and the body's motion with respect to the foot will be symmetric. We call that location the *neutral point*. (a) When the foot is displaced backward from the neutral point, the system accelerates forward. (c) Displacing the foot forward from the neutral point causes the system to decelerate. The algorithm for controlling forward speed is based on a model with no friction, a massless leg, and a symmetrical pattern of leg thrust. See Raibert [22] for details.

where T_s is the expected duration of the next stance phase, $\dot{x}_s$ is the expected forward speed during the stance phase, $\dot{x}_f$ is the present forward speed during flight, $\dot{x}_d$ is the desired forward speed for the next flight phase, and $k_{\dot{x}}$ is an empirically determined gain. For the experiments described in this paper, the control system estimated the forward running speed during the next stance phase to be

$$\dot{x}_s = \frac{k(\dot{x}_f + \dot{x}_d)}{2}. \tag{3}$$

This estimate takes into account that the forward running speed does not instantaneously change from the current value to the desired value, but changes gradually throughout the stance phase. This estimate also includes a model of the normal pattern of deceleration and acceleration as the body passes over the foot. The constant k was 0.74 for the trials reported in this paper. More details of the forward speed control are given in Raibert [22] and Hodgins [4].

Flight Duration Method—With constant forward speed, the duration of the flight phase determines the distance traveled during flight. The duration of the flight phase is determined by the vertical velocity of the system when the foot leaves the ground and the difference between the altitude of the body at liftoff and touchdown. If the altitude of the body is the same at touchdown and liftoff, the duration of the flight phase is

$$T_f = \frac{2\dot{z}_{lo}}{g} \tag{4}$$

where $\dot{z}_{lo}$ is the vertical velocity at liftoff and g is the acceleration of gravity.

The components of the system energy that influence the flight duration are

$$E = \frac{1}{2}m\dot{z}_{lo}^2 + mgz_{lo} \tag{5}$$

where z_{lo} is the vertical altitude of the body at liftoff and m is the mass of the system. We assume that the kinetic energy due to the horizontal motion of the body is constant and the kinetic energy due to the rotation of the body and legs is negligible. Combining (4) and (5), we obtain an equation for the desired energy as a function of the desired flight duration

$$E = \left(z_{lo} + \frac{gT_f^2}{8}\right)mg. \tag{6}$$

The control system manipulates the thrust delivered by the leg during stance so that the energy at liftoff is the desired value. The thrust is delivered throughout the stance phase with a pattern designed to leave the forward speed unchanged. The thrust replaces energy lost to mechanical impacts and friction and produces the desired changes in the duration of the flight phase from one step to the next. The control system adds energy in a function that approximately matches the shape of the force in the leg during stance. During the time interval t_i to t_{i+1} the energy added is

$$\Delta E = \int_{r_{hl}(t_i)}^{r_{hl}(t_{i+1})} F_r \dot{r}_{hl} \tag{7}$$

where F_r is the force in the leg and r_{hl} is the length of the hydraulic actuator. Because ΔE and F_r have approximately the same shape, $\dot{r}_{hl}$ is nearly constant. The hydraulic valves on the legs of the planar biped are flow-control valves and produce a flow and actuator rate proportional to the signal sent to the valve.

Stance Duration Method—The distance the body travels during the stance phase is the product of the average forward running speed and the duration of the stance phase. The duration of the stance phase is determined, to first order, by the spring-mass oscillator formed by the system mass bouncing on the stiffness of the leg. The duration of the stance phase is approximately one half cycle of the natural oscillation, $T_s \approx \pi/\omega_0$, where ω_0 is the natural frequency of the system. The natural frequency is approximately $\sqrt{k/m}$, where k is the effective stiffness of the leg's pneumatic spring and m is the mass supported by the leg spring (upper leg, body, and other leg).

The control system manipulates the stiffness of the leg by controlling the resting air pressure in the leg spring during the flight phase. Data from experiments with the running machine were used to find an empirical relationship between the resting pressure of the air spring and the duration of the

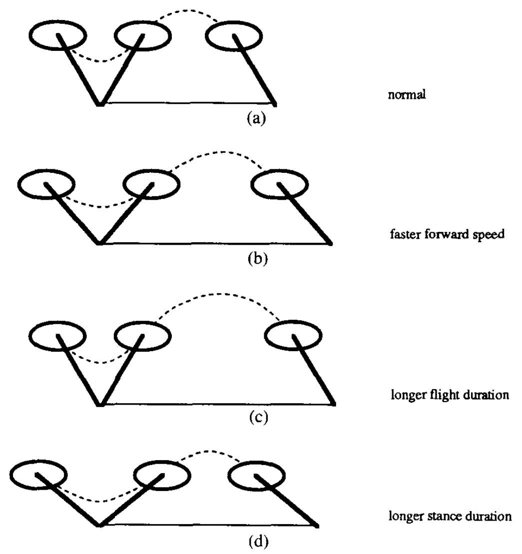

Fig. 7. Three methods for controlling step length. (a) portrays a normal step. (b)-(d) show longer steps produced by adjusting one of the parameters of the step. (b) has increased forward speed, (c) an extended flight phase, and (d) an extended stance phase. In each case, increasing one of the parameters of the step produces a longer step length.

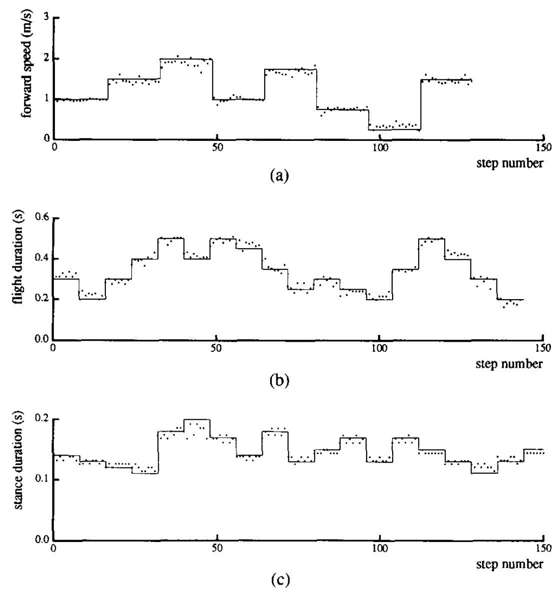

Fig. 8. Data showing the control of the adjusted parameters. In each experiment, two of the three parameters were held constant at nominal values while the third was adjusted according to a stored pattern of desired values. The solid lines show the desired values for the adjusted parameter and the dots represent the value that was actually generated on each step. (a) Control of forward running speed. The biped ran for 16 steps at each desired forward speed. Then the desired speed was changed to the next value in the pattern. The average absolute error in forward speed was 0.06 m/s. The nominal values were $T_s = 0.14$ s and $T_f = 0.47$ s. (b) Control of the duration of the flight phase. The average absolute error in flight duration was 0.03 s. $\dot{x} = 1.2$ m/s, $T_s = 0.15$ s. (c) Control of the duration of the stance phase. The average absolute error in stance duration was 0.005 s. $\dot{x} = 1.0$ m/s, $T_f = 0.38$ s.

stance phase. Higher pressures cause the spring to be stiffer and reduce the duration of the stance phase. This relationship is observed to be independent of vertical velocity and forward speed at touchdown, except when the spring is very soft. The control system manipulates the stance duration by adjusting the resting pressure of the pneumatic leg spring. Variations in stance duration are used to manipulate the distance traveled during the stance phase and thereby the step length.

The three methods for controlling step length are illustrated in Fig. 7. Each method adjusts one parameter of the running cycle to produce the desired step length, leaving the other two parameters unchanged. The best control of step length will probably be achieved by combining the three methods to adjust several parameters at once. However, in order to learn more about each method, we measured the effects of adjusting just one parameter at a time.

We performed two experiments for each method of controlling step length. In the first experiment, the control system specified a pattern of desired values for the adjusted parameter while keeping the desired values for the two unadjusted parameters fixed at a nominal setting. The purpose of this experiment was to measure the accuracy with which the adjusted parameter—forward speed, flight duration, or stance duration—could be controlled. In the second experiment, the control system specified a pattern of desired step lengths. A desired value for the adjusted parameter was determined on each step based on the desired steplength and the nominal values used for the unadjusted parameters. The purpose of this experiment was to measure the precision with which step lengths could be controlled. Precise control of step length requires that the unadjusted parameters do not vary in reaction to manipulations of the adjusted parameter. For instance, when the foot is positioned to control forward speed, the action must not disturb the duration of the stance or flight phases.

V. Results

To measure the precision of control for the adjusted parameters, the control system specified a pattern of desired values for the adjusted parameter while specifying fixed nominal values for the two unadjusted parameters. The nominal values were approximately $T_{f,\text{nom}} = 0.4$ s, $T_{s,\text{nom}} = 0.15$ s, and $\dot{x}_{\text{nom}} = 1.1$ m/s. These nominal values provided an operating point about which all manipulations were made. Results are given in Fig. 8 for the three methods. Fig. 8(a) plots the pattern of desired forward speeds (solid line) and the forward speed that was actually achieved on each step (dots). The forward speed ranged between 0.25 and 2.0 m/s, with an average absolute error of 0.06 m/s, or 5% of the nominal forward running speed. Fig. 8(b) plots the results of a similar experiment for flight duration. Flight durations varied between 0.2 and 0.5 s. The average absolute error in flight duration was 0.03 s, or 7.5% of the nominal flight duration. Fig. 8(c) plots the results for the control of stance duration. The desired stance durations varied between 0.1 and 0.2 s. The pressure varied between 10 and 100 lbf/in^2 resulting in an effective leg stiffness that varied between 5000

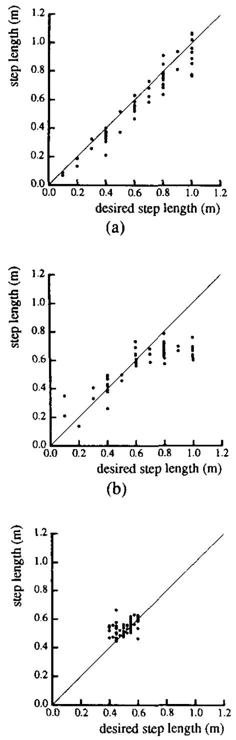

Fig. 9. Scatter plot of actual step length against desired step length for each method. In each experiment the machine ran forward using one of the three methods to follow a pattern of desired step lengths. (a) Forward speed method. The desired step lengths ranged between 0.1 and 1.0 m. The average absolute error in step length was 0.07 m. Nominal values were $T_f = 0.4$ s and $T_s = 0.15$ s for this experiment. (b) Flight duration method. The pattern of desired step lengths was the same as that used in the forward speed method experiment. The average absolute error in step length was 0.07 m when the desired step length was within the range of step lengths possible through adjustments in flight duration with the given forward speed and stance duration. $\dot{x} = 1.1$ m/s, $T_s = 0.15$ s. (c) Stance duration method. The desired step lengths ranged between 0.4 and 0.6 m. The average absolute error in step length was 0.03 m when the desired step length was within the range of step lengths possible with adjustments in stance duration with the given forward speed and flight duration. $\dot{x} = 1.1$ m/s, $T_f = 0.33$ s.

and 14 000 N/m. The average absolute error in stance duration was 0.005 s, or 3% of the nominal stance duration.

To measure the control of step length, the control system specified a pattern of desired step lengths. Fig. 9 shows the results for each of the three methods. For the forward speed method, step lengths varied between 0.1 and 1.1 m, with an average absolute error of 0.07 m, or 12% of the nominal step length, (which was 0.6 m = $\dot{x}_{\text{nom}} (T_{f,\text{nom}} + T_{s,\text{nom}})$). Fig. 9(b) plots data for the flight duration method. The average absolute error in step length was 0.07 m, 12% of nominal. Fig. 9(c) plots data for the stance duration method. The average absolute error in step length was 0.03 m, 5% of the nominal step length. The error measurements for each method were made by including only those step lengths that were within the range obtainable by the method.

The three methods for controlling step length relied on maintaining two of the parameters constant at nominal values while the third was adjusted. We examined the variations in the nominal parameters for these three experiments and found that, for the forward speed and flight duration methods, the nominal parameters were approximately constant as required. The error in each nominal parameter varied but was generally less than 10% except for stance duration in the flight duration method, which had an error of 13%.

The data in Fig. 9 illustrate several characteristics of the three methods for step length control. First, the error in step length depended on the magnitude of the step length. For example, the step length error obtained by the forward speed method was larger for longer steps than for shorter steps. The control of forward speed was less accurate at higher speeds, as indicated by an increased step length error for longer steps. Second, each of the methods had a saturation point beyond which increases in desired step length were not matched by increases in achieved step length. Such saturation is clear in Fig. 9(b), where step length did not increase beyond about 0.6 m. These saturation limits are not absolute, in that they depend on the choice of nominal control parameter values. For example, if the nominal forward speed were doubled, then the maximum step length for the flight duration method would double to about 1.2 m. Third, Fig. 9(c) shows that the error in step length was approximately equal to the range of achievable step lengths for the stance duration method. This limited range is primarily responsible for the poor performance of this method.

The three methods for controlling step length can be compared in terms of accuracy and range. Accuracy is a measure that reflects the error between the desired and actual step length. Range is the difference between the minimum and maximum possible step length. The accuracy of a method determines the foothold size that could be used successfully by the legged system. If a legged system were to use a foothold 0.1 m long and 1.0 m distant, it would need to take a step of 1.0 m with an error of less than ± 0.05 m. Otherwise, it would not land on the foothold.

Good accuracy does not guarantee that a method will be successful in controlling step length. The controller must also be able to vary step length over a wide range. For example, if a system were running with a step length of 1 m but no acceptable foothold lay 1 m ahead, the system would have to take a shorter or longer step to avoid stepping on the undesirable region of the terrain. If the undesirable region were large, the required adjustment might be substantial.

Table I gives the minimum and maximum step lengths obtained with each method. Adjusting forward speed produced a variation in step length that was twice as large as that obtained by manipulating flight duration and more than ten times that obtained by manipulating stance duration. The range of each method was affected by the range of the adjusted parameter as well as by the nominal values selected for the two unadjusted parameters. The range of any of the methods could be manipulated by changing the nominal values of the three parameters. The nominal values used for the experiments were chosen to be in the middle of the range for each parameter and provided an operating point at which all three variables were well controlled.

TABLE I
MAXIMUM AND MINIMUM VALUES FOR THE STEP LENGTHS PRODUCED BY EACH METHOD AND THE MEAN, STANDARD DEVIATION, AND MAXIMUM OF THE ERROR IN STEP LENGTH FOR EACH METHOD

Control Method	Step Length Minimum	Step Length Maximum	Step Length Range	Error in Step Length Mean	Error in Step Length Standard Deviation	Error in Step Length Maximum
Forward Speed	0.00 m	1.10 m	1.10 m	0.05 m	0.07 m	0.27 m
Flight Duration	0.32 m	0.72 m	0.40 m	−0.04 m	0.09 m	0.22 m
Stance Duration	0.55 m	0.66 m	0.11 m	−0.01 m	0.04 m	0.14 m

Table I also gives the mean, standard deviation, and maximum of the error in step length for each method. Forward speed and flight duration were tested using the same pattern of desired step lengths, but the error calculation included only those step lengths that fell within the range of the method. A smaller range of desired step lengths was used to test the stance duration method so that more data points would lie within the achievable range of the method. Manipulating stance duration provided the most accurate control, with a mean of -0.01 m, a standard deviation of 0.04 m, and a maximum error of 0.14 m. Manipulating forward speed and flight duration provided less accurate control of step length, but that control was provided for a much larger range of step lengths.

Range and accuracy are not the only criteria for choosing a method for controlling step length. The demands of the task may determine which methods are feasible. For example, a long jumper might want to avoid controlling step length through adjustments in forward speed if those adjustments would reduce the forward speed at the takeoff board and the length of the subsequent jump. Similarly, the flight duration of the steps preceding a vertical jump may affect the height of the jump. As these examples illustrate, the control system may need to vary the method for controlling step length depending on the constraints of the rough-terrain task.

The fourth method for controlling step length, direct placement, provides precise foot placements on a single step when the displacement from the balance foothold is not too large. We found that the planar biped usually recovered its balance if the displacement from the balance foothold on a single step was less than 0.1 m when the machine was running at 1 m/s. Direct placement fails, however, when the foot must be placed accurately on a series of footholds. The disturbances caused by direct placement generally accumulate on each step, thereby making balance more and more difficult to maintain. In an experiment in which the control system switched from using one step length to a slightly longer one using direct placement the forward speed decreased more on each step and the biped fell over after a few steps.

Despite the drawbacks of direct placement, it has two appealing features. First, the control occurs at the last possible moment—just before the final touchdown that determines the length of the step. Therefore, direct placement is ideal for error recovery when crucial information about the terrain is received very late in the cycle. Second, direct placement is much simpler to implement than the other three methods for controlling step length. Direct placement does not require complicated models or predictions of the system's behavior. As long as the desired foothold is within reach, the foot can be placed on it at touchdown. This feature makes direct placement very accurate.

VI. COMBINING METHODS

How might the three methods for adjusting step length be combined to increase the range of available step lengths and reduce the error in foot placements? Range will increase if more than one parameter is varied at a time. For example, increasing both the flight duration and the forward speed to their maximum values would produce a longer step than increasing only one. To improve accuracy, the change in step length could be allocated so that each parameter was near the center of its working volume or in the region of its working volume where control is most accurate.

Accuracy could also be improved by combining one of the three methods for controlling step length with direct placement. Any of the three methods could be combined with direct placement for a single step. Adjustments in flight duration and stance duration could be combined with direct placement for many steps in a row. Adjustments in forward speed and direct placement cannot be combined for many steps in a row because both manipulate the placement of the foot with respect to the hip.

For high accuracy on a single step, one of the three methods for controlling step length could be used to move the balance foothold close to the desired terrain foothold; then direct placement could be used to place the foot precisely on the desired foothold. The separation between the balance foothold and the actual placement would be small enough for the system to regain its balance on subsequent steps. We tested this combined method for the task of stepping on a target with good results.

Direct placement could also be combined with adjustments in flight duration or stance duration to produce more accurate step lengths on several consecutive steps. On each step the foot could be placed directly on the desired foothold, generating a predictable although undesired change in forward speed. The control system could pick a flight or stance duration for the following step that would produce a step of the correct length despite the change in forward speed. The control system could also choose a flight or stance duration that, when combined with direct placement on the next touchdown, would drive the forward speed back toward its nominal value. We have not tested either of these hybrid methods.

If forward speed were controlled in some other fashion, such as adjustments in hip torque, then adjustments in forward speed and direct placement might be used on the same step to produce a wide range of accurately controlled step lengths. McGeer [12] proposed such a method for foot

TABLE II
MEAN, STANDARD DEVIATION, AND MAXIMUM OF THE ERROR IN PLACING THE LEFT FOOT ON A TARGET

Control Method	Number of Trials	Mean	Error at Target Standard Deviation	Maximum
Random Foot Placements	none	0.000 m	0.320 m	0.55 m
Forward Speed	21	−0.004 m	0.023 m	0.05 m
Flight Duration	20	−0.051 m	0.046 m	0.13 m
Forward Speed + Direct Placement	25	0.001 m	0.004 m	0.01 m
Flight Duration + Direct Placement	25	0.000 m	0.005 m	0.02 m

(The machine began adjusting step length about 5 m before reaching the target. Only the error in step length on the target step was included in the calculated error. The first line of the table shows the expected mean, standard deviation, and maximum of the error at the target with no control operational, assuming a uniform distribution of foot placements.)

placement during walking. He also suggested that foot placement during running could be controlled with adjustments in either hip torque or thrust. Using linearized step-to-step equations, McGeer [11] argued that adjusting thrust is much more effective for controlling step length than adjusting hip torque.

VII. Demonstrations

A. Step on Target

Using the three methods to adjust the length of its steps, the planar biped ran on simple rough terrain. One task was to place a particular foot on a target foothold. This task is similar to the one faced by a long jumper who must step accurately on the takeoff board to obtain the longest possible jump. To perform this task, the biped began adjusting its step length about 5 m before it reached the target foothold. The control system adjusted the step length to land on a pattern of invisible stepping stones evenly spaced along the path to the goal. The distance between the stepping stones was chosen to be as close as possible to the current step length to minimize the change in step length. The pattern of stepping stones was not recalculated on each step as the machine approached the target.

With no control of step length, the footfalls would have been uniformly distributed around the circle. The distance between the target and the nearest footfall would be uniformly distributed with a range of plus or minus the step length (± 0.55 m) and the standard deviation of the error would be 0.32 m. When the control system used the forward speed method for adjusting step length, the mean and standard deviation of the error in foot placement were -0.004 and 0.023 m. Data for the flight duration method are given in Table II. The nonzero mean was the result of a systematic error in the control of flight duration and therefore in the control of step length. This error could be eliminated by adding an offset to the control algorithms. We tested direct foot placement in conjunction with the forward speed and flight duration methods. In both cases, foot placement errors were essentially eliminated, as shown in Table II. Whatever disturbances direct placement caused to the stability of the system in these experiments were generally not visible to us when we watched the biped perform this task.

B. Leap over Obstacle

The biped leapt over obstacles by adjusting the length of its steps as it approached the obstacle. The approach was much like the place-foot-on-target demonstration just described. The control system adjusted step length on the approach to align the machine appropriately with the obstacle prior to the leap. When it reached the target takeoff point, the biped jumped high and shortened its legs to increase clearance. The machine has jumped over a rectangular obstacle 0.36 m high and 0.32 m long on 15 consecutive attempts. It has also jumped through a C-shaped hoop.

C. Climb Stairs

The biped has run up and down a flight of three stairs, as shown in Fig. 10. As the machine approached the stairs, the forward speed method was used to place a foot on a target foothold just below the first step. During the climb up and down the stairs, the control system used adjustments in forward speed to match step lengths to the stair tread depth, and it manipulated flight duration to account for stair riser heights. The precision of step length control was degraded during stair climbing, due to the changing altitudes of the footholds. The decreased thrust required to maintain the flight duration during the descent of the stairs caused the duration of the stance phase and the forward running speed to decrease more than was expected, and this error resulted in shorter steps than expected. Despite these limitations, the machine usually climbed the stairs successfully and on one occasion ran up and down the stairs on seven consecutive trials.

VIII. Conclusions

A legged system must control the length of its steps if it is to use isolated footholds on rough terrain. This paper explores three methods for controlling step length in the context of an actively balanced dynamic legged system. Each method adjusts a parameter of the running cycle, leaving the others set to nominal values. The parameters were forward running speed, running height, and duration of ground contact.

We measured the performance of each method for controlling step length. The forward speed method produced the widest range of step lengths. The flight duration method produced steps with about half the range of the forward speed method. The stance duration method produced step lengths with a tenth of the range produced by the forward speed method. When each method was tested with a pattern of desired step lengths that fell entirely within the range of the method, the stance duration method produced the highest accuracy. However, the range of step lengths provided by the stance duration method is so small that it seems unlikely to be useful for rough terrain locomotion. The forward speed method provided the best combination of wide range and high accuracy.

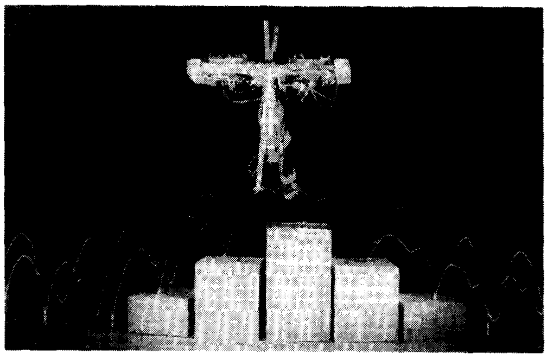

Fig. 10. Photograph of the planar biped running up and down a flight of three stairs. The control system adjusts the length of the machine's steps so that the feet land approximately in the center of each stair. The machine is shown running from right to left at about 0.5 m/s. Light sources indicate the paths of the feet. Each stair is 0.18 m (7 in) high and 0.30 m (12 in) deep.

An alternative approach to adjusting the foot placement was to ignore balance for a single step, placing the foot directly on the desired foothold and recovering balance later. This approach generally resulted in very precise foot placements for a single target but could not be used to control many steps in a row.

It remains to factor out the degree to which these results are affected by the particular characteristics of the experimental apparatus and other elements of the implementation.

Acknowledgment

B. Brown, K. Brennan, J. Koechling, J. Miller, and D. Barrett made important contributions to this project, for which the authors are grateful. About half of this work was done while the authors were in the CMU Computer Science Department and the Robotics Institute.

References

[1] E. A. Devjanin, *et al.*, "The six-legged walking robot capable of terrain adaptation," *Mechanisms Machine Theory*, vol. 18, pp. 257-260, 1983.

[2] V. S. Gurfinkel *et al.*, "Walking robot with supervisory control," *Mechanisms Machine Theory*, vol. 16, pp. 31-36, 1981.

[3] S. Hirose, "A study of design and control of a quadruped walking vehicle," *Int. J. Robotics Res.*, vol. 3, pp. 113-133, 1984.

[4] J. K. Hodgins, "Legged robots on rough terrain: Experiments in adjusting step length," Ph.D dissertation, CMU-CS-89-151, Carnegie-Mellon Univ., Pittsburgh, PA, 1989.

[5] J. K. Hodgins, J. Koechling, and M. H. Raibert, "Running experiments with a planar biped," in *Robotics Research: The 3rd Int. Symp.*, O. Faugeras and G. Giralt, Eds. Cambridge, MA: MIT Press, 1986.

[6] J. K. Hodgins and M. H. Raibert, "Biped gymnastics," in *Robotics Research: The 4th Int. Symp.*, B. Bolles and B. Roth, Eds. Cambridge, MA: MIT Press, 1987.

[7] J. Koechling and M. Raibert, "How fast can a legged robot run?" in *Symp. Robotics*, DSC vol. 11, K. Youcef-Toumi and H. Kazerooni, Eds. New York: Amer. Soc. Mechanical Eng., 1988.

[8] D. N. Lee, J. R. Lishman, and J. A. Thomson, "Regulation of gait in long jumping," *J. Exp. Psychol.*, vol. 3, pp. 448-459, 1982.

[9] R. A. Liston, "Walking machine," *J. Terramechan.*, vol. 3, pp. 18-31, 1964.

[10] '—,"Increasing vehicle agility by legs: The quadruped transporter," presented at 38th Nat. Meeting Operations Res. Soc. Amer., 1970.

[11] T. McGeer, "Passive bipedal running," Simon Fraser Univ., Rep. CSS-IS TR 89-02, 1989.

[12] T. McGeer, "Powered flight, child's play, silly wheels, and walking machines," presented at IEEE Conf. Robotics Automat., Scottsdale, AZ, 1989.

[13] R. B. McGhee, "Robot locomotion with active terrain accommodation," in *Proc. Nat. Science Foundation Robotics Res. Workshop.* (Univ. of Rhode Island, Kingston, RI), 1980.

[14] —, "Vehicular legged locomotion," in *Advances in Automation and Robotics*, G. N. Saridis, Ed. Greenwich, CT: JAI Press, 1983.

[15] R. B. McGhee and G. I. Iswandhi, "Adaptive locomotion of a multilegged robot over rough terrain," *IEEE Trans. Syst. Man Cybern.*, vol. SMC-9, pp. 176-182, 1979.

[16] R. S. Mosher, "Test and evaluation of versatile walking truck," in *Proc. Off-Road Mobility Res. Symp.* (Int. Soc. Terrain Vehicle Systems, Washington, DC), 1968, pp. 359-379.

[17] D. E. Okhotsimski, V. S. Gurfinkel, E. A. Devyanin, and A. K. Platonov, "Integrated walking robot development," presented at Conf. Cybernetic Models of the Human Neuromuscular System (Engineering Foundation), 1977.

[18] D. E. Okhotsimski and A. K. Platonov, "Control algorithm of the walker climbing over obstacles," presented at Int. Joint Conf. Artificial Intell. (Stanford, CA), 1973.

[19] —, "Perceptive robot moving in 3D world, in *Proc. 4th Int. Joint Conf. Artificial Intell.* (Tbilisi, U.S.S.R) Sept. 3-8, 1975.

[20] F. Ozguner, S. J. Tsai, and R. B. McGhee, "An approach to the use of terrain-preview information in rough-terrain locomotion by a hexapod walking machine," *Int. J. Robotics Res.*, vol. 3, pp. 134-146, 1984.

[21] A. E. Patla, C. Robinson, M. Samways, and C. J. Armstrong, "Visual control of step length during overground locomotion: task-specific modulation of the locomotor synergy," *J. Exp. Psychol.*, vol. 15, no. 3, 1989.

[22] M. H. Raibert, *Legged Robots That Balance*. Cambridge, MA: MIT Press, 1986.

[23] K. J. Waldron and R. B. McGhee, "The adaptive suspension vehicle," *IEEE Control Syst. Mag.*, vol. 6, no. 6, pp. 7-12, 1986.

[24] W. H. Warren, Jr., D. N. Lee, and D. S. Young, "Visual control of step length during running over irregular terrain," *J. Exp. Psychol.: Human Perception and Performance*, vol. 12, no. 3, pp. 259-266, 1985.

Jessica K. Hodgins received the B.A. degree in mathematics from Yale University, New Haven, CT, in 1981 and the Ph.D. degree from Carnegie-Mellon University, Pittsburgh, PA, in 1989. Her Ph.D. dissertation was entitled "Legged Robots on Rough Terrain: Experiments in Adjusting Step Length."

From 1989 to 1990, she was a postdoctoral researcher at the Leg Laboratory, part of the MIT Artificial Intelligence Laboratory, where she continued her studies on the dynamics of legged locomotion. In the fall of 1990, she joined the Computer Animation Systems Group at the IBM Thomas J. Watson Research Center, Yorktown Heights, NY. She is studying control algorithms that can be applied to physically accurate models to produce realistic computer animations of dynamic motor tasks.

Marc H. Raibert (M'79) received the B. S. Degree in electrical engineering from Northeastern University, Boston, MA, in 1973 and the Ph.D. degree from the Massachusetts Institute of Technology, Cambridge, in 1977. His Ph.D. dissertation, entitled "Motor control and learning by the state space model," was done in the MIT Artificial Intelligence Laboratory and the Department of Psychology.

He worked on robot sensing and control at the Jet Propulsion Laboratory and Caltech from 1977 through 1980. He moved to Carnegie-Mellon University, Pittsburgh, PA, in 1981, where he joined the Computer Science Department and the Robotics Institute. He is currently Professor of Electrical Engineering and Computer Science at MIT. He is a member of the Artificial Intelligence Laboratory and the Department of Brain and Cognitive Sciences. His research is devoted to the study of systems that move dynamically. He studies the principles of legged locomotion as they apply to robots and animals, the theory of passive dynamic systems, and the use of control for computer animation. He is the author of *Legged Robots That Balance* (MIT Press).

Dr. Raibert is on the Editorial Board of the *International Journal of Robotics Research*, and is a Fellow of the AAAI.