M. H. Raibert
Associate Professor,
Department of Computer Science and
The Robotics Institute.

H. B. Brown, Jr.
Senior Engineer,
The Robotics Institute.

Carnegie-Mellon University,
Pittsburgh, Pa. 15213

Experiments in Balance With a 2D One-Legged Hopping Machine

The ability to balance is important to the mobility obtained by legged creatures found in nature, and may someday lead to versatile legged vehicles. In order to study the role of balance in legged locomotion and to develop appropriate control strategies, a 2D hopping machine was constructed for experimentation. The machine has one leg on which it hops and runs, making balance a prime consideration. Control of the machine's locomotion was decomposed into three separate parts: a vertical height control part, a horizontal velocity part, and an angular attitude control part. Experiments showed that the three part control scheme, while very simple to implement, was powerful enough to permit the machine to hop in place, to run at a desired rate, to translate from place to place, and to leap over obstacles. Results from modeling and computer simulation of a similar one-legged device are described by Raibert [10].

I. Introduction

A key to the mobility obtained by legged systems that are dynamically stabilized is their ability to remain upright without a broad continuous base of support. The ability to locomote on a narrow base permits travel where obstructions are closely spaced, or where the only support path is a narrow one. The ability to locomote using intermittent support, or support points that are separated from one another gives flexibility to the choice of where and when to place the feet. For instance in rough terrain feet are placed only on those locations that provide good support, even when they are separated by large distances. Biological legged systems routinely take advantage of these features of dynamic stability, narrow base and intermittent support to traverse terrain that can not be traversed by wheel or tread.

Previous experimental work on balance began with Cannon's control of inverted pendulums that rode on a small powered truck [3]. His experiments included balance of a single pendulum, two pendulums one atop the other, two pendulums side by side, and a long limber pendulum. Matsuoka [7] implemented a very simple one-legged hopping machine that lay on a table inclined 10 deg from the horizontal. Kato et al. [5] have studied quasi-dynamic walking in the biped. In their studies a 40 kg biped with 10 hydraulically driven degrees of freedom used a preplanned motion to dynamically transfer support from one foot to the other. Miura and his students [9] built an electrically powered biped that balanced itself in 3D using a tabular control scheme. With only three actuated joints it used a shuffling gait to balance that reminds one of Charlie Chaplin. There have been numerous experimental studies of legged systems that are statically stable [6, 8, 4, 13, 12].

The present study explores the control of a physical one-legged hopping machine. The objective of using a machine with only one leg was to avoid the problem of coordinating many legs, thereby simplifying the experiments, while at the same time drawing attention to the issues of dynamic stability that are central to versatile legged systems. Study of a one-legged system also addressed the question of intermittent support in locomotion, because the only gait available was hopping. A related objective was to explore the use of springy legs in obtaining efficient hopping, as animals do [1]. Springy legs permit energy to be recovered from one step so that it may be used to power the next step. Experimental results obtained from a physical device with one springy leg confirm the feasibility of the control strategies, previously tested only in simulation, as reported by Raibert [10].

This paper reports experimental results obtained by controlling a physical one-legged device, which is described in the next section. Section 3 describes how control of the device can be decomposed into three simple parts, and presents the three corresponding control algorithms. Data are presented in Section 4 that were obtained by using the three algorithms to control the hopping machine. They illustrate the ability of the algorithms to control hopping height, to maintain balance, to regulate travel from place to place, to respond to sudden disturbances, and to leap. Section 5 closes the paper with conclusions and a summary.

II. The One-Legged Device

The 2D hopping machine shown in Fig. 1 was designed and constructed to do experiments in balance. Its main parts are a body and a leg connected by a simple hip. There is also a mechanism that constrains motion of the hopping machine to two dimensions. The body consists of a platform that mounts sensors, valves, actuators and computer interface electronics, and a weighted beam that increases the moment of inertia of the body.

The leg consists of a double acting air cylinder with a

Contributed by the Dynamic Systems and Control Division for publication in the Journal of Dynamic Systems, Measurement, and Control. Manuscript received by the Dynamic Systems and Control Division, January 13, 1983.

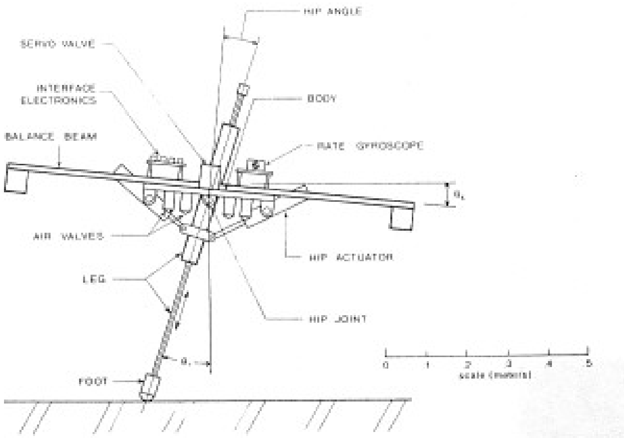

Fig. 1 The one-legged device used for experiments has two primary parts: a body and a leg. The body provides mounting for valves, electronics and sensors, and has a balance beam that increases its moment of inertia. The leg is a double ended air cylinder that pivots with respect to the body, and that carries a padded foot on one end of the rod. Four two-way pneumatic valves control flow of compressed air to and from each end of the leg cylinder. Air can be trapped in the cylinder to make it act like a spring. Another set of pneumatic actuators powered by a proportional servo valve acts between the leg and body to control angle of the hip. On board sensors measure length of the leg, angle between leg and body, angle between leg and ground (only during stance), contact between foot and ground, pressure in the leg air cylinder, and inclination of the body with respect to the vertical.

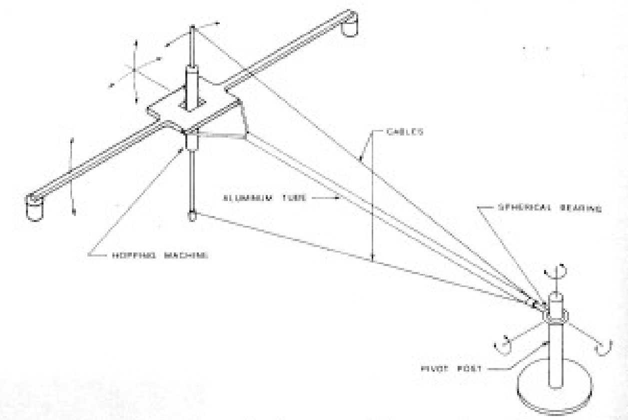

Fig. 2 Tether boom mechanism constrains motion of one-legged device to surface of a sphere. The tether consists of a section of aluminum tubing with a spherical bearing at the stationary pivot end, and a fork pivot at the hopper end. The main boom holds the hopper 2.5 m from the pivot center, giving it radial and yaw stability, while a pair of nylon cables prevent roll. These cables also keep the foot a nearly constant radius from the pivot point as the leg changes length, minimizing radial scrubbing. Instrumentation mounted at the pivot provides measurement of the three primary motions: vertical translation, horizontal translation, and rotation about the axis of the boom.

rubber cushion attached to the lower end of the rod to form a foot. The narrow foot, about 1 cm when fully loaded, provides a good approximation to a point of support. The coefficient of friction between the foot and the floor in our laboratory is about 0.6. Delivery of air pressure to the top end of the cylinder drives the piston and rod assembly downward, providing the vertical thrust for hopping. The leg air cylinder acts as a spring when the valves controlling air flow seal it off. This air cushion provides an opportunity to transfer the kinetic energy from one hop to the next hop, thereby reducing the energy cost of continuous hopping.

Under the best test condition the air spring recovered about 65 percent of the energy from one hop and returned it to the next hop. The ratio of body mass to the mass of the reciprocating portion of the leg is about 20:1. This results in a 5 percent energy loss when the device lands on the ground, and when it leaves the ground, as explained in [10]. Friction in the leg actuator accounts for the other hopping losses.

The leg and body are connected by a hinge-type pivot joint that forms a hip. The angle between body and leg at the hip is controlled by a single stage proportional air servo valve that drives a pair of single acting air cylinders. A potentiometer provides a measurement of this angle to the control computer that servos the joint with a simple linear servo:

$$\tau(t) = K_{P,FL}(\varphi - \varphi_d) + K_{V,FL}(\dot{\varphi}) \qquad (1)$$

where

- $\tau(t)$ is the actuator torque generated at the hip,
- φ is the angle of body with respect to the leg, $\varphi = (\theta_2 - \theta_1)$
- φ_d is the desired leg angle, and
- $K_{P,FL}, K_{V,FL}$ are position and velocity gains during flight. (Values given in the Appendix.)

A full 40 deg sweep of the leg takes approximately 120 ms. The ratio of moment of inertia of the body to that of the leg is 15:1. This relatively high ratio ensures that the orientation of the leg may be changed during flight without severely disturbing body attitude. The center of gravity of the body is located at the hip, so the only moments acting on the body are those generated by the hip actuator.

Motion of the hopping machine is constrained to the 2D surface of a large sphere by the tether boom shown in Fig. 2. This mechanism permits the hopping machine to translate vertically and horizontally, and to rotate about the axis of the tether boom. Since the tether boom is made of cables and lightweight tubing, weight and friction are sufficiently small to be ignored. The tether boom arrangement permits the machine to travel around the laboratory on a circle of radius 2.5 m. Sensors mounted on the tether boom pivot provide measurements of the three free motions. An umbilical is attached to the tether boom that carries compressed air to drive the actuators, as well as electrical power and communication with the control computer.

Sensors mounted on the hopping machine provide state information to a nearby control computer and permit performance to be measured. Potentiometers measure the angle between body and leg, the angle between leg and ground, and the length of the leg. A switch mounted on the foot senses contact with the ground. A pressure transducer measures compression of air in the leg air cylinder. A rate gyroscope mounted on the body of the hopper senses its angular rate. This signal is also integrated to estimate attitude of the body with respect to the ground; this estimate is periodically corrected for drift using the combined leg and hip angle measurements. The pitch motion to which the gyroscope is sensitive is also measured by instrumentation of the tether boom.

To make the machine hop the leg actuator is pressurized during the stance phase of each cycle and partially exhausted during the flight phase. The timing of pressure and exhaust are chosen to excite the spring-mass oscillator formed by the leg and body. Peak to peak amplitude of body oscillation can be varied between .04 and .3 m, with corresponding bouncing frequencies of about 3 to 1.5 per second. Over this range of bouncing frequencies the stance period is nearly constant varying by only a few percent, as expected for a spring-mass system.

To make the machine balance while traveling from place to place, the foot is positioned during flight and the hip is torqued during stance. During flight, a forward position for the foot is chosen appropriate to the machine's rate of travel. During stance, torques are developed at the hip to maintain the body's upright posture. The resulting control system produces running at rates of up to 1.2 m/s (2.7 mph) with strides of up to .6 m. General operation of the machine is shown in Fig. 3. These photographs, taken in rapid sequence

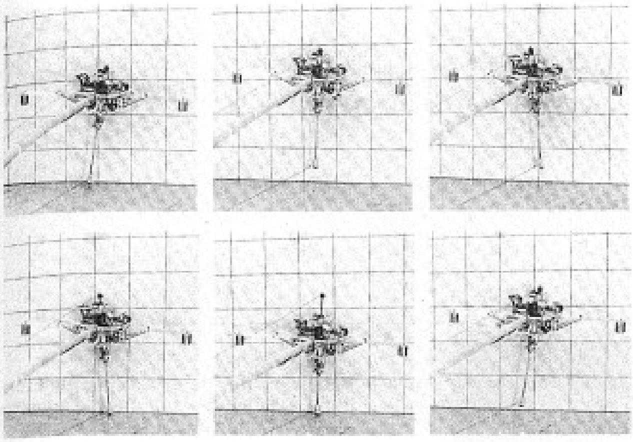

Fig. 3 Sequence of photos showing one complete stride of the hopping machine running from left to right. Background grid spacing is .2 m. Running speed here is .75 m/s. Stride .45 m, stride period 680 ms. Adjacent frames separated by 100 ms.

throughout one stride, show the machine running at .75 m/s (1.7 mph). The distance traveled by the center of gravity during stance is:

$$x_{CG} = \dot{x} T_{ST} \tag{2}$$

where

$\dot{x}$ is the horizontal velocity of the body, assumed to be constant, and
T_{ST} is the duration of the stance phase.

The locus of points over which the center of gravity travels during the stance period, called the *CG-print*, extends from x_{TD} to $x_{TD} + x_{CG}$, where x_{TD} is the horizontal position of the center of gravity at touch-down. To minimize the tipping moment during stance, the foot should be placed in the center of the *CG*-print. This is accomplished by positioning the leg during flight so that the foot is the specified horizontal distance from the hip:

$$\Delta x = \frac{\dot{x} T_{ST}}{2} \tag{3}$$

where

Δx is the horizontal distance between foot and hip at touch-down. (See Fig. 4.)

This foot position causes the horizontal and vertical motions of the leg to be symmetrical about the midpoint of the stance interval, at which point the leg is vertical and maximally compressed. This symmetry during stance is given by:

$$\theta_1(t_{TD}+t) = \theta_1(t_{LO}-t) \tag{4}$$

$$w(t_{TD}+t) = w(t_{LO}-t) \tag{5}$$

where

$w(t)$ is the distance from the hip to the foot,
t_{TD} is the time of touch-down, and
t_{LO} is the time of lift-off.

Tipping moments and forward accelerations are also nearly symmetrical, and therefore average to zero.

When the foot lands precisely in the center of the *CG*-print, forward velocity is not changed. To accelerate the system, either to compensate for velocity errors or to change speed, a tipping moment is purposely generated. When the foot is placed forward of the center of the *CG*-print, then the device will tend to tip backward, which slows it down. If the foot is placed to the rear of the center of the *CG*-print, then it will tip forward, increasing forward velocity. A linear function of

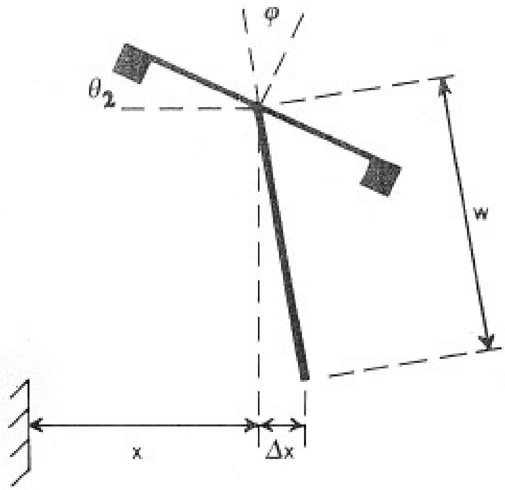

Fig. 4 Diagram that shows variables used in calculating placement of the foot during flight

velocity error is used to generate deviations in foot placement from the center of the *CG*-print:

$$x_{ERR} = K(\dot{x} - \dot{x}_d) \tag{6}$$

where

$\dot{x}_d$ is the desired value for $\dot{x}$ and
K is a feedback gain.

Augmenting (3) with (6) yields:

$$\Delta x = \frac{\dot{x} T_{ST}}{2} + K(\dot{x} - \dot{x}_d) \tag{7}$$

To achieve the desired foot placement at touch-down, the angle between leg and body must be controlled during flight. The hip angle that will yield the specified foot position is given by:

$$\varphi_d = \theta_2 - \text{Arcsin}\left[\frac{\dot{x} T_{ST} + 2K(\dot{x} - \dot{x}_d)}{2w}\right] \tag{8}$$

The algorithm based on (8) has limitations at high velocity. As long as $\Delta x << w_{MAX}$ and $\theta_{1,MAX}$ is small, horizontal forces generated by compression of the leg are small and (8) is reasonably accurate. However, this condition is not satisfied in fast running. In that case $\Delta x_{TD} \sim w_{MAX}$ and $\theta_{1,MAX}$ is large; horizontal forces decelerate the system during the first half of stance, then accelerate it during the second half, making the average forward velocity during stance less than the overall average. Under these circumstances the *CG*-print is substantially shorter than estimated by (8). As a practical matter this problem was avoided by substituting the average value of $\dot{x}$ during stance in (8) for the overall average.

Attitude Control. Since angular momentum of the system is conserved during flight, the control system can manipulate attitude of the body only during stance when ground forces act on the foot. Torques generated during stance between the leg and body can be used to servo the attitude of the body to any desired orientation:

$$\tau(t) = K_{P,ST}(\theta_2 - \theta_{2,d}) + K_{V,ST}(\dot{\theta}_2) \tag{9}$$

where

$K_{P,ST}, K_{V,ST}$ are position and velocity gains used for the hip servo during stance, and
$\theta_{2,d}$ is the desired attitude of the body, zero in this paper.

Sequence Control. For a legged system to locomote each leg must alternate between a support phase in which the foot touches the ground and bears weight, and a transfer phase

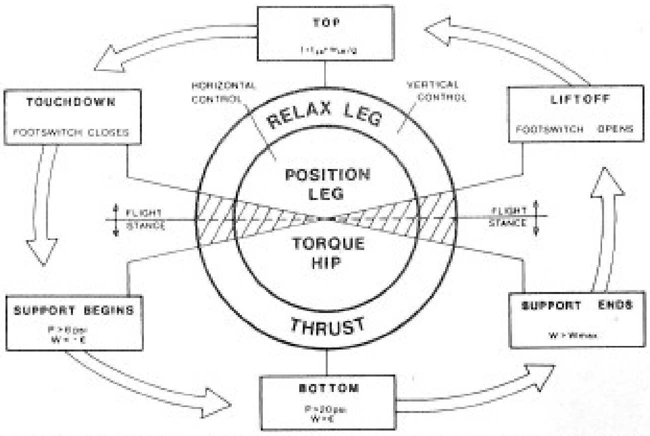

Fig. 5 Finite state controller uses sensor measurements to synchronize the various phases of control with the cyclic activity of the locomotion system. Actions of the height, velocity, and attitude controls are coordinated by this state controller as it sequences through the hopping cycle.

when the foot is elevated to move from one foothold to another. At the heart of the control system lies a sequencer that ensures such an alternation by coordinating height, velocity, and attitude controllers to the timing of the machine's support and transfer phases. This coordination relies on sensors that signal the transition from one phase to another. For example, support begins when pressure begins to build in the leg cylinder, and the leg begins to shorten. The remaining transitions and transition states for the hopping cycle are shown in Fig. 5.

As the hopping system nears the ground two events happen in rapid succession. First there is contact with the ground, then the leg bears a load. Contact is important because horizontal motions of the leg required for foot placement during flight should not continue when the foot is very close to the ground. If they do, then unwanted torques may be generated inadvertently on the body, upsetting its attitude. Since friction between foot and ground develops in proportion to the normal force, generation of hip torques to control the attitude of the body must await adequate vertical loading. For these reasons the time between first contact and load-bearing support is treated as a *twilight-zone* during which thrust, foot placement, and attitude control processes are inoperative. Another *twilight-zone* occurs when the system leaves the ground. Lift-off begins and attitude control ends when extension of the leg is nearly complete. However, to ensure that the foot is fully unloaded before it is moved, no torques are generated at the hip until the foot switch opens.

The precautions taken during touch-down and lift-off to avoid motion of the foot when it is not fully loaded are not optimal for high speed running. When running at high speed the foot should not merely be left motionless during touch-down, but should accelerate to match the relative speed of the moving ground before actually touching it. At lift-off the foot should continue moving backward until it is fully unloaded. Running animals such as the kangaroo and cat match their feet to ground speed in this way [1], but the hopping machine has not yet been made to do so.

IV. Experimental Results

The experimental hardware and control algorithms described above were used to verify the effectiveness and workability of the three-part control decomposition, to evaluate and refine the control algorithms, and to demonstrate balance in a man-made running system. The height, velocity, and attitude control algorithms and the sequence controller of the last section were implemented in a set of control programs that ran on a minicomputer. They controlled the hopping machine and recorded its behavior. The experiments tested vertical hopping, horizontal travel, and leaping.

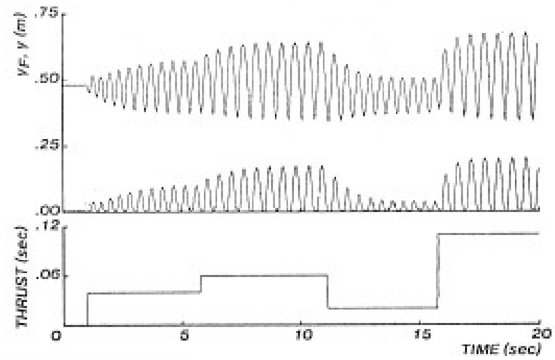

Fig. 6 Data recorded while hopping machine hopped in placed. Every 5 seconds duration of vertical thrust was adjusted to change hopping height. In each case it took about 2 seconds and 4 cycles to adjust. Upper curve) Elevation of hip, y. Middle curve) Elevation of foot, y_F. Lower curve) Duration of thrust. (a323.10).

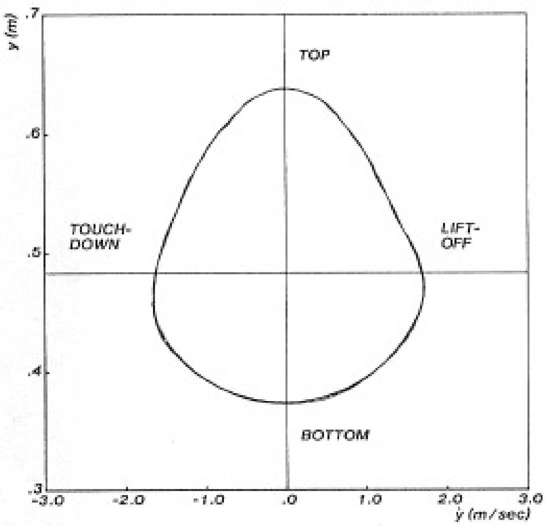

Fig. 7 Four cycles from Fig. 6 replotted in phase diagram form. The curves cross the axes at LIFT-OFF, TOP, TOUCH-DOWN, and BOTTOM. Note that the vertical position of the hip is plotted on ordinate, the vertical velocity of the hip on abscissa, and time progresses in counterclockwise direction. (a344.1)

Vertical Hopping. To demonstrate control of hopping height, data were recorded by the control computer while a new height setpoint was specified every 5 seconds. The results are plotted in Fig. 6. Each time the setpoint was changed it took four or five hops for the height to stabilize. In these records the machine hopped vertically in one place with no translation. Four cycles of these data are replotted in the y versus $\dot{y}$ phase plot of Fig. 7. The indentation at the upper right is due to the sudden acceleration experienced by the body when the leg was accelerated to body speed. The upper part of this diagram is parabolic due to gravity's constant acceleration, while the lower part would be harmonic for a linear spring. Since the air spring is *hard*, the trajectory is not quite harmonic.

Horizontal Travel. We examined the system's ability to regulate rate of translation during running by having the control computer specify a ramp in desired velocity while recording. The results are plotted in Fig. 8. These data show the machine, first hopping in place, then running at increasing rates up to about .9 m/s. Throughout the run velocity was controlled to within about .25 m/s of the desired value. This accuracy is typical. It was possible to improve velocity

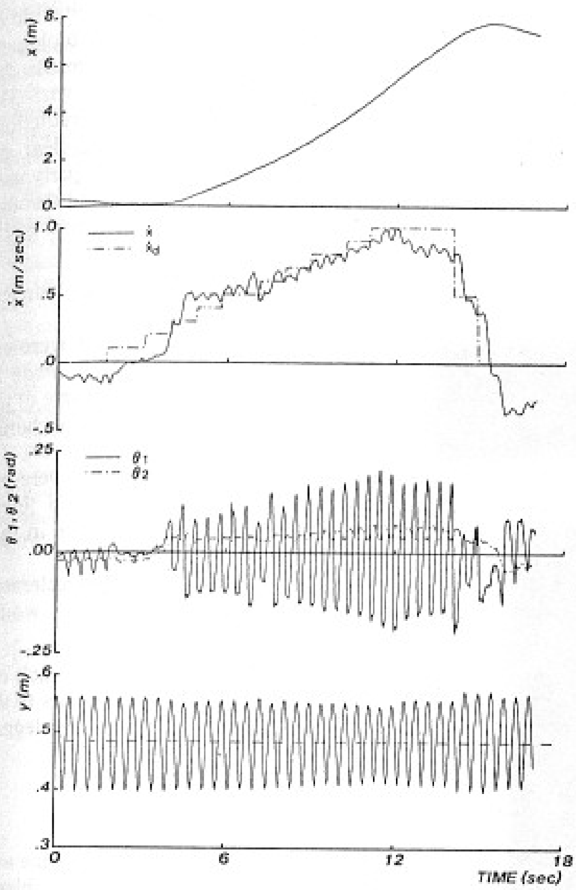

Fig. 8 Rate control of the hopping machine was tested by varying $\dot{x}_d$, the rate set point (shown stippled), along a ramp from 0. to 1.0 m/s in 10 s. The maximum speed obtained in this trial over an entire stride was about .95 m/s (2.1 mph). Dashed line on y curve separates stance, data below line, from flight. (a337.12)

regulation at lower rates by reducing the velocity error gain of (7), and at higher rates by increasing this gain. With a high velocity error gain, stable running at 1.2 m/s (2.7 mph) was obtained for a few seconds at a time. Algorithms that use nonlinear velocity error feedback provided promising results, but were not adequately developed to be included here.

During running, the leg and body counter-oscillate as shown in the plots of θ_1 and θ_2. The back and forth motions of the leg were not explicitly programmed, but resulted from interactions between the velocity controller that operated during flight, and the attitude controller that operated during stance. Oscillations of the body are to be expected because angular momentum is conserved during flight, and attitude correction occurs only during stance.

The plot of θ_2 also shows that average body angle deviated from zero, the setpoint, in rough proportion to running speed. These deviations were very small, typically only a few degrees, even for rapid running. The average deviation of body inclination from the desired value could be further minimized by taking the expected body rotation into account when specifying the setpoint used by the attitude controller:

$$\theta'_{2,d} = \theta_{2,d} + \frac{I_1}{I_2}\,\mathrm{Arcsin}\left(\frac{\dot{x}T_{ST}}{2w}\right) \tag{10}$$

where

I_1, I_2 are the moments of inertia of the leg and body, respectively.

Hopping height and stride frequency were also affected by running speed, as indicated by the plot of body altitude, y.

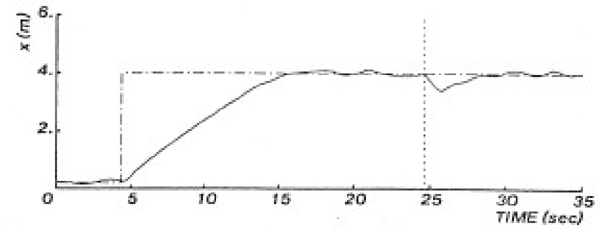

Fig. 9 Position control was achieved by manipulating desired rate of translation, as described in text. After 4.3 seconds of stationary hopping the computer specified a 4 meter step change in desired position. (Vertical dotted line): Experimenter disturbed the machine by delivering a sharp horizontal jab with his hand. It returned to the setpoint within a few seconds. (a324.19)

Actually, the relevant factor is not running speed directly, but the angle of the leg at touchdown.

Faster running resulted in large deviations of the leg from vertical, and therefore, shallower hops. These shallower hops took less flight time resulting in more rapid stepping. At 0.9 m/s peak foot clearance was reduced by 20 percent, and stride period was reduced by 8.6 percent. This result is reminiscent of data showing that kangaroos hopped at slightly higher frequency as their forward velocities increased [2].

A position controller was used to make the hopping machine translate from place to place. Position control was implemented with a controller that transformed position errors into desired velocities:

$$\dot{x}_d = K\min\{(x - x_d), x_{\max}\} \tag{11}$$

This algorithm prevented the machine from attempting very rapid translations when it was far from the target. Desired positions were sometimes specified with a joystick that was manipulated by the operator, and sometimes specified by the control computer according to a preplanned sequence. Data obtained while the device was position controlled are plotted in Fig. 9. A limit cycle of about $\pm .1$ m is present whenever the machine is hopping in place.

Also shown in this Fig. 9 is the response to an external disturbance. After about 25 seconds the experimenter delivered a sharp horizontal jab to the body as the machine hopped in place. (See dotted vertical line in figure.) Balance was recovered and the machine returned to its commanded position after a few seconds. The control system tolerated fairly strong disturbances of this sort, provided the forces exerted on the body were primarily horizontal. Disturbances that introduced large rotations of the body often led to a crash.

Leaping. A specialized vertical control program was used to make the hopping machine leap while the standard velocity and attitude controls operated normally. During such experiments the machine approaches the obstacle with a moderate running rate. One step before the obstacle the operator presses the *leap* button, initiating a preplanned sequence synchronized to vertical hopping:

1. During the next stance phase, thrust is delayed so that the leg shortens more than normal under load of the body. This is done to prepare for a hop of maximum height. Thrust begins at bottom, not stopping until the leg has fully lengthened.
2. Once airborne, the leg shortens and its swinging motion is delayed; both provide extra clearance.
3. When top is reached hip angle is servoed to the correct landing angle as usual. There is less time to position the foot than normal, but the shorter leg is moved more quickly due to its reduced moment of inertia.
4. The leg is lengthened in preparation for landing.
5. Upon landing, the standard hopping sequence is re-established.

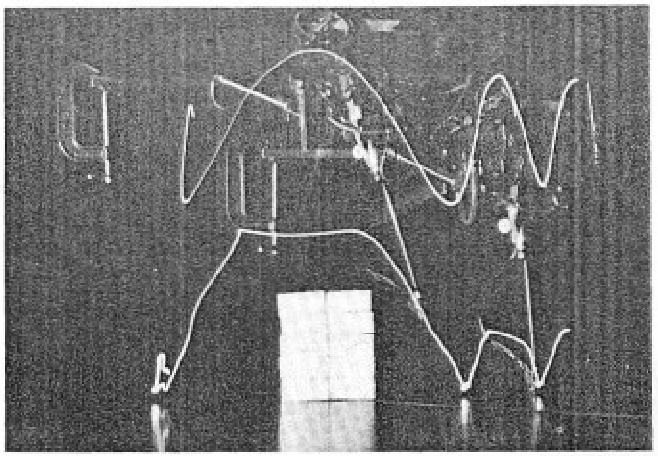

Fig. 10 Hopping machine leaping over an obstacle. Machine approaches from right. The leaping sequence is described in text. Travel continues to the left after leap. Obstacle is .19 m tall and .15 m wide. The photograph was made with a low frequency strobe, while small light sources indicated paths of the foot and hip.

During the leaping sequence, velocity and attitude controls continued to operate in the usual manner.

This procedure was used to leap over a stack of styrofoam blocks, as shown in Fig. 10. While many successful leaps were obtained in this manner, equally many resulted in crashes. Clearing an obstacle requires that the foot be placed quite precisely before the leap, that the leap have sufficient altitude, and that the leap have sufficient span. The existing algorithm does a good job with height and span, but has no means for adjusting the take-off point.

The task of placing the foot on a particular spot is more demanding than merely controlling the average forward velocity. In order to position the foot for take-off, it will be necessary to plan and control how the foot is positioned during a number of steps before the leap. This might be accomplished by adjusting the desired velocity of the system as it approaches the obstacle, or by adjusting leg stiffness. We are exploring these sorts of techniques for foot placement as part of our effort to understand locomotion on rough terrain.

V. Discussion

While the primary purpose of using a one-legged apparatus for these experiments was to focus on balance, an additional goal was to develop a model that could explain the behavior of each leg in more complicated systems that run. If we ignore the third dimension, generalizing from the one-legged machine to the two-legged hopping kangaroo is very easy. A direct comparison can be made between the motions of the hopping machine's one leg and the motions of the kangaroo's pair of legs. The primary difference is that the kangaroo uses its tail to help compensate for the large sweeping motions of the legs, so that the body need not react by pitching so much on each hop. The control system can still regulate hopping height, body attitude, and velocity as before.

Many characteristics of the running biped are also similar to the running one-legged machine, including the alternation betweeen stance and flight, the regular vertical oscillations, and the periods of support by only one leg. In the case of the biped, the two legs always swing in opposite directions, making rotations of the body or a tail unnecessary. Think of a biped as a hopping machine that substitutes a different leg on each stride. The three part decomposition can be employed as before. The three part control system can also be used to understand how a quadruped runs. This is described elsewhere by Raibert and Sutherland [11].

The specific algorithms described in this paper might be useful in discovering the locomotion mechanisms used by biological systems. While the parallels between behavior of the one-legged hopping machine and various biological systems are provocative, the mechanisms responsible for control in biological systems are still not known. The algorithms described in this paper allow specific predictions that could be explored experimentally. The most clear cut predictions are that hip torque during stance is uniquely used to adjust body attitude, and that speed is controlled through placement of the feet. The following experiments might elucidate these questions:

- Examine kinematic data to determine if human runners position their feet according to (7).
- Suppose a human running at constant speed were externally accelerated forward during flight, or made to think he was accelerated forward. Would the angle of the leg with respect to the vertical at touch-down change according to the algorithm given above?
- Suppose a human running at constant speed were externally rotated forward during flight, with no linear acceleration of the *CG*. Would leg angle change in that case?
- If the body of a running human were linearly accelerated during stance without disturbing body attitude, would there be a correction before the next step?

We do not know if it is technically feasible to do such experiments, but the results could provide important clues to the mechanisms responsible for balance in existing legged systems.

VI. Conclusions

This paper describes an experimental hopping machine and a set of experiments designed to elucidate the basic problems of dynamic stability and balance in legged systems that hop and run. The present work was done in order to verify the correctness of principles originally developed in simulation, and to get practical experience that might some day be valuable in designing a practical vehicle.

It was found that control of the one-legged hopping machine can be decomposed into three separate parts that are synchronized by the behavior of the machine. One part controls hopping height by choosing a fixed amount of energy to inject on each hopping cycle. A second control part regulates the forward travel of the system by placing the foot a specific distance in front of the hip as the device approaches the ground on each step. The third controller corrects the attitude of the body by applying appropriate torques to the hip during stance when vertical loading permits horizontal forces to be generated at the foot. A finite state sequencer provides the glue that synchronizes the actions of the three controllers to the ongoing behavior of the device.

Experiments showed that the relatively simple control algorithms obtained good control of the machine. They maintained consistent hopping heights, reaching equilibrium after a change within a few hopping cycles. The device ran at speeds of up to 1.2 m/s. At low velocity, speed regulation was rather poor, but improved when traveling at higher rates. The machine traveled from place to place using position control. A modification to the vertical control algorithm enabled the machine to leap over small obstacles.

Acknowledgments

This research was sponsored by the Systems Science Office of the Defense Advanced Research Projects Agency under contract MDA903-81-C-0130, and by a grant from the System Development Foundation. We are indebted to Mike Chepponis, Gene Hastings, and Jeff Miller for their many contributions in the laboratory.

References

1 Alexande
Kangaroos (Ma
2 Dawson,
Kangaroos," N
3 Higdon,
Multiple-Outpu
ASME Winter
4 Hirose, S
Quadruped W
Angeles, 1980.
5 Kato, T.,
of the Quasi-D
posium on Theo
6 Kenny, J.
for High Effic
Society Annual
7 Matsuoka
Movements,"
8 McGhee,
9 Miura, F
Mechanism,"
10 Raibert,
Simulation for
Cybernetics, in

References

1 Alexander, R. McN., and Vernon, A., "The Mechanics of Hopping by Kangaroos (Macropodidas)," *J. Zool., London*, Vol. 177, 1975, pp. 265–303.

2 Dawson, T. J., and Taylor, C. R., "Energetic Cost of Locomotion in Kangaroos," *Nature*, Vol. 246, 1973, pp. 313–314.

3 Higdon, D. T., and Cannon, R. H., Jr., "On the Control of Unstable Multiple-Output Mechanical Systems," *Proc. of Winter Annual Meeting*, ASME Winter Annual Meeting, 1963.

4 Hirose, S., and Umetani, Y., "The Basic Motion Regulation System for a Quadruped Walking Vehicle," ASME Conference on Mechanisms, Los Angeles, 1980.

5 Kato, T., Takanishi, A., Jishikawa, H., and Kato, I., "The Realization of the Quasi-Dynamic Walking by the Biped Walking Machine," 4th Symposium on Theory and Practice of Robots and Manipulators, IFTMoM, 1981.

6 Kenny, J. D., Space General Corp., "Investigation for a Walking Device for High Efficiency Lunar Locomotion," *Proceedings of American Rocket Society Annual Meeting*, Philadelphia, 1965.

7 Matsuoka, K., "A Mechanical Model of Repetitive Hopping Movements," *Biomechanisms*, Vol. 5, 1980, pp. 251–258, In Japanese.

8 McGhee, R. B., and Buckett, J. R., "Hexapod," *Interface Age*, 1977.

9 Miura, H., and Shimayama, I., "Computer Control of an Unstable Mechanism," *J. Fac. Eng.*, Vol. 17, 1980, pp. 12–13, In Japanese.

10 Raibert, M. H., "Hopping in Legged Systems—Modelling and Simulation for the 2D One-Legged Case," *IEEE Tran. Systems, Man, and Cybernetics*, in press, 1983.

11 Raibert, M. H., and Sutherland, I. E., "Machines That Walk," *Scientific American*, Vol. 248, No. 1, 1983, pp. 44–53.

12 Russell, M., Jr., "Odex I: The First Functionoid," *Robotics Age 5*, Vol. 5, 1983, pp. 12–18.

13 Sutherland, I. E., *A Walking Robot*, The Marcian Chronicles, Inc., P.O. Box 10209, Pittsburgh, Pa. 15232, 1983.

APPENDIX

Physical Parameters of One-Legged Hopping Machine

Leg mass–1.31 kg
Leg moment of inertia–.036 kg-m^2

Body mass–7.18 kg
Body moment of inertia–.52kg-m^2

$K = .035$m/(m/s)

$K_{P,ST} = 153.$ Nt-m/rad
$K_{V,ST} = 14.$ Nt-m/(rad/s)

$K_{P,FL} = 47.$ Nt-m/rad
$K_{V,FL} = 1.26$ Nt-m-/(rad/s)