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Active

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Center # : 10/24-6-R7924-0A0 Center shr #: 10/22-1-F7924-0A0 OCA file #:
Work type : RES
Contract#: IRI-9309189 Mod #: INITIATION Document : GRANT
Prime #: Contract entity: GTRC

Subprojects ? : N CFDA:
Main project #: PE #:

Project unit: GVU Unit code: 02.010.314
Project director(s):
HODGINS J K COMPUTING (404)894-3152

Sponsor/division names: NATL SCIENCE FOUNDATION / GENERAL
Sponsor/division codes: 107 / 000

Award period: 930901 to 970228 (performance) 970531 (reports)

Sponsor amount	New this change	Total to date
Contract value	99,909.00	99,909.00
Funded	99,909.00	99,909.00
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Title: RIA: DEVELOPING REFLEXES FOR ROBOTS-STUMBLING & FUMBLING

PROJECT ADMINISTRATION DATA

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Security class (U,C,S,TS) : U ONR resident rep. is ACO (Y/N): N
Defense priority rating : N/A NSF supplemental sheet
Equipment title vests with: Sponsor GIT X

Administrative comments -
INITIATION OF PROJECT. FUNDS PROVIDED BY THIS AWARD INCLUDE SUPPORT FROM ARPA.

PROJECT CLOSEOUT - NOTICE

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(3)

Closeout Notice Date 07-JUL-1997

Project Number C-50-638 Doch Id 32633

Center Number 10/24-6-R7924-0A0

Project Director HODGINS, JESSICA

Project Unit GVU

Sponsor NATL SCIENCE FOUNDATION/GENERAL

Division Id 3393

Contract Number IRI-9309189 Contract Entity GTRC

Prime Contract Number

Title RIA: DEVELOPING REFLEXES FOR ROBOTS-STUMBLING & FUMBLING

Effective Completion Date 28-FEB-1997 (Performance) 31-MAY-1997 (Reports)

Closeout Action:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	N	
Final Report of Inventions and/or Subcontracts	N	
Government Property Inventory and Related Certificate	N	
Classified Material Certificate	N	
Release and Assignment	N	
Other	N	

Comments
LETTER OF CREDIT APPLIES. 98A SATISFIES PATENT REPORT.

Distribution Required:	
Project Director/Principal Investigator	Y
Research Administrative Network	Y
Accounting	Y
Research Security Department	N
Reports Coordinator	Y
Research Property Team	Y
Supply Services Department	Y
Georgia Tech Research Corporation	Y
Project File	Y

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April 3, 1995

Mr. Howard Moraff
Division of Information, Robotics, and Intelligent Systems
National Science Foundation
1800 G Street NW
Washington DC 20550

Dear Howard:

I am enclosing a copy of a paper on our recent work on slipping in bipedal robots to serve as an progress report for my research initiation award, NSF Grant No. IRI-9309189. This paper was accepted for publication at the IEEE/RSJ International Conference on Intelligent Robot and Systems in August and reflects our results to date on this project.

Please let me know if you need any additional information.

Sincerely,

Jessica Hodgins
Assistant Professor

JKH:jcm
Enc.

C-50-638

To appear in the IEEE/RSJ International Conference on Intelligent Robot and Systems, August 1995

Reflexive Responses to Slipping in Bipedal Running Robots

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Many applications require the traversal of uneven or unmodelled terrain. This paper explores strategies for one kind of rough terrain: slippery surfaces. We evaluate several reflexive responses to slipping in the context of a dynamic simulation of a three-dimensional bipedal robot. There are two classes of reaction strategies. One group of strategies continues the step in which the slip occured. The other group lifts the slipping foot and repositions the legs for another attempt. The best performing strategy positions the legs in a fixed trianglular configuration on the step following a slip.

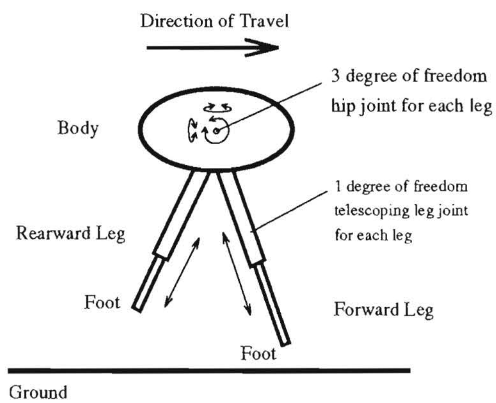

Figure 1: **Biped Structure.** The bipedal robot consists of a body and two telescoping legs. Each leg has three degrees of freedom at the hip and a fourth degree of freedom for the length of the leg. The mass of the body is larger than the masses of the legs, allowing control of the legs without large fluctuations in body attitude.

Introduction

Robust control algorithms that allow legged robots to negotiate the rough and unmodelled terrain found in most natural and many human-made environments have not yet been designed. Rough terrain, ground in which stable footholds are not immediately available, occurs both in natural environments and in environments that have been constructed or modified for human use. Legged robots lack the sophisticated control techniques that would allow them to behave robustly on even simple rough terrain such as stairs, curbs, grass, and slopes. Topographies that include small obstacles, loose particles, and slippery areas multiply the difficulty of successful traversal. This paper explores one component of the rough terrain problem: slippery surfaces.

Sensing the surface properties of terrain before making contact is a difficult problem, compounded by the noisy and approximate nature of information obtained at a distance. Robust locomotion on rough terrain requires that the robot be responsive to unexpected surface features, including holes, steps, bumps, debris, and sticky or slippery areas. In this paper we explore reflexive strategies for responding to unmodelled slippery terrain. We explore these strategies by implementing them for a dynamic simulation of a three dimensional running biped robot.

The simulation tasks presented below involve recovering from a single slip. We consider several reflexive responses to slipping, including some strategies that try to recover in one step and some that abandon the slipping step to attempt a recovery on the next step by repositioning the legs. Trials with varying friction and forward velocity are used to compare the strategies. The results of these simulations demonstrate that reactions that continue the slipping step produce the smallest errors but are limited to surfaces with friction coefficients above 0.45. The leg repositioning strategies are capable of recovering from surfaces with coefficients as low as 0.05.

Rough Terrain Locomotion

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.

One example of successful outdoor rough terrain locomotion is the Adaptive Suspension Vehicle built at Ohio State University (Waldron and McGhee 1986). This vehicle is 5.2 m long, 2.4 m wide, 3.0 m high and weighed 2700 kg. An operator rides on the ASV to provide general speed and direction inputs, while leg coordination and foothold selection are provided by control computers. A range sensor that provides terrain depth information for the 10 m of terrain in front of the vehicle is used in foot placement and obstacle avoidance. This machine is able to walk up and down grassy slopes, through a muddy cornfield, and over railroad ties.

Bares and Whittaker (1993) describe gaits for rough terrain navigation by the Ambler, a fully autonomous, orthogonal-legged hexapod walking robot. Built at Carnegie Mellon University, Ambler uses vertically sliding legs to decouple movement actuators from support actuators. This arrangement aligns actuator forces with the the actuator displacements, eliminating backdriving and increasing efficiency. By keeping the body level, the planning space is reduced to four degrees of freedom. Approximately 3.0 m long, 4.5 m wide, and 5.0 m high, the 3180 kg robot has traversed several kilometers on rough terrain. The robot walks with several gaits which vary in stability, stride length, and efficiency.

Klein and Kittivatcharapong (1990) discuss the problem of allocation of forces over multiple legs to achieve desired motion or resultant forces and torques on the body of the robot. They proposed algorithms for ensuring that foot forces remain within the friction cone and identifying situations in which these constraints, or the desired body forces and torques, could not be achieved. Their work addressed prevention of slipping and did not consider sensor noise or responses to unmodelled surfaces.

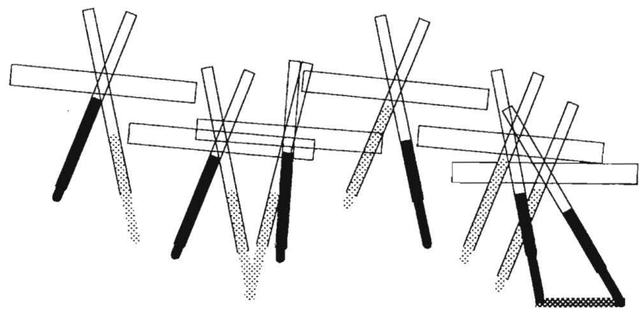

Figure 2: **Physical Biped Slip.** Planar two-legged robot running across an oily spot on the laboratory floor. Without strategies for reacting to unmodelled slippery areas, the foot slides forward and fails to provide support for the body. The drawings show the configuration of the robot as recorded by the computer during a laboratory experiment. One leg is drawn in black, the other in grey. The horizontal line indicates the path of the foot as it skids on the floor.

For dynamically stable robots, the control of step length for rough terrain locomotion interacts with the control of balance. Hodgins and Raibert (1991) implemented three methods for controlling step length of a running biped robot, given a model of the terrain. Each method adjusted one parameter of the running cycle: forward running speed, running height, or 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 with accurate control of step length. 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.

Reflexive Responses to Errors

Biological systems use many different reflexes in locomotion and manipulation. Reflexes help to restore balance when perturbations occur during walking or standing (Nashner 1976, 1977, 1980). The role of reflexes in walking is complex: the same stimulus will elicit a different response in the stance phase than in the swing phase (Forssberg 1979; Forssberg, Grillner, Rossignol, and Wallen 1976; Belanger and Patla 1984). During the swing phase, touching the foot of a cat or human will cause the leg to flex so as to raise the foot. If an obstacle caused the stimulus, this response might lift the foot over the obstacle and allow walking to continue. During the stance phase, a stimulus delivered to the foot will cause the leg to push down harder, resulting in a shorter stance phase. Although these actions are opposite, both facilitate the continuation of locomotion.

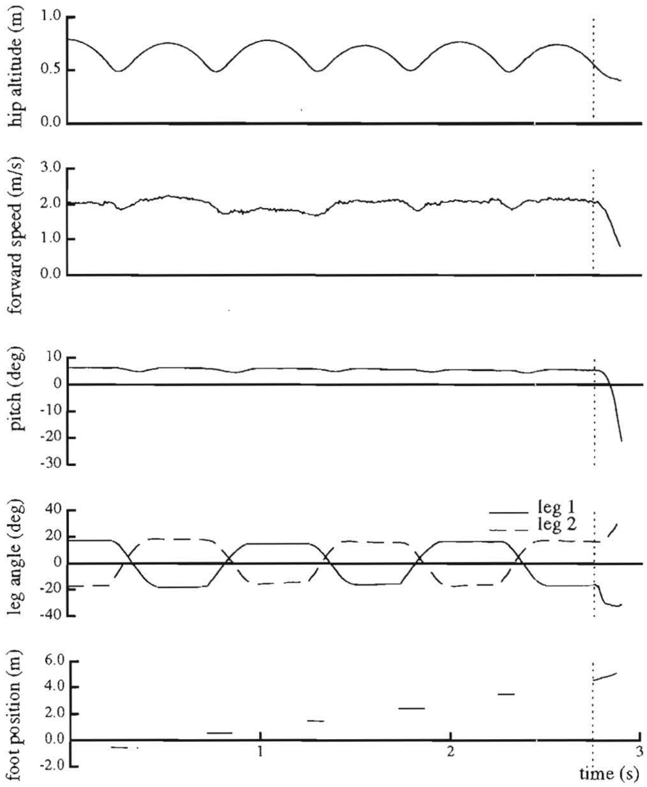

Figure 3: **Slipping Data of the Physical Robot.** These plots show the physical planar robot slipping on oil during a laboratory experiment. The first five steps show running on a high friction floor. In the final step, the foot slipped on the floor and the machine collapsed. The vertical lines indicate when the foot began to slip. The top three graphs show the orientation and forward speed of the body. The bottom two graphs show the leg angles of both legs and the position of each foot on the ground. For each step but the last the foot is stationary while it is on the ground.

Robotics has adopted the term "reflex" from the biological literature but in both biology and robotics, the precise definition of the term varies from study to study. Most researchers in robotics use the term to mean a quick response initiated by sensory input. Some require that reflexes are open-loop and proceed independently of subsequent sensory input (Tomovic and Boni 1962; Bekey and Tomovic 1986); others use the term more loosely to describe actions that are performed with feedback until a terminating sensory event occurs (Wong and Orin 1988). In some cases, reflexes refer to general purpose actions (Hirose 1984; Brooks 1989) and in others only to actions taken to correct errors or compensate for disturbances (Wong and Orin 1988).

Hirose (1984) built and controlled a statically stable quadruped that used reflexive actions to walk over simple forms of rough terrain without visual input or a terrain map. The control system used a probing reflex to climb over objects and to walk up and down steps. A leg moved forward slowly until a contact sensor mounted on the foot detected an obstacle. The foot was raised a fixed amount and then continued its forward motion. When the leg had swung far enough forward, the foot was lowered until a load cell indicated that the leg was bearing an adequate load. This probing strategy is similar to the elevator reflex observed in locusts (Pearson and Franklin 1984).

Link	Mass (kg)	Moment of Inertia (x, y, z kgm^2)		
Body	23.2	0.9	0.9	0.602
Upper Leg	1.4	0.0185	0.0173	0.0014
Lower Leg	0.64	0.0197	0.0197	0.000176

Table 1: Parameters of the rigid body model of the bipedal robot. The moment of inertia is computed about the center of mass of each link.

Wong and Orin (1988) implemented two reflex responses for a prototype leg of the Ohio State University Adaptive Suspension Vehicle. Using velocity and hydraulic pressure information from sensors at the joints, they were able to detect foot contact and foot slippage. In keeping with the reflex model, the detection and resulting action were kept simple so the control system could respond quickly. In bench tests, the foot contact reflex was successfully used to reduce the peak forces at touchdown, and the foot slippage reflex was used to detect and halt slipping.

Tomovic and Boni (1962) used a reflex response to implement grasping for the Belgrade prosthetic hand. Touch sensors on the fingers, thumb, and palm initiated the motion. When the fingers were touched, the hand closed in a pinch grasp with the finger tips and thumbs touching the object. When the palm was touched, the motion of the thumb was delayed and the object was encircled by the fingers.

Bekey and Tomovic (1986) continued the exploration of prosthetic control systems that resembled biological control systems. Their technique, called *artificial reflex control*, was rule-based and relied on sensory data and stored response patterns. After the response pattern was initiated, subsequent sensory data were ignored. The motions were of fixed magnitude independent of the initial stimulus. This control system was used for a prosthetic device for a single leg above-the-knee amputee where the motion of the other leg provided the corrections necessary for balance.

Link	COM to Proximal (m)	COM to Distal (m)
Body		0.0
Upper Leg	0.095	-0.095
Lower Leg	0.221	

Table 2: The distance from the center of mass of each link to the distal and proximal joints in z for the canonical configuration of the robot (the distance in x and y is zero for this model).

Brooks's subsumption architecture (Brooks 1989) uses an approach that combines many simple reflex-like actions to produce more complex behaviors. He has implemented complicated actions like six-legged walking through many interacting behaviors. One reflex specifies that feet that are off the ground should be swung forward while the other legs are swung back. A global gait generator specifies the movement order of the legs while inhibitory connections between the legs prevent conflicting reflexes from acting simultaneously.

Nagle (1994) developed algorithms for running on terrain that was known to be slippery. By running slowly, foot forces were nearly vertical. His controller used a priori knowledge or estimation of friction coefficients to prevent slipping by confining control forces and torques to slip-free regions. Nagle evaluated the performance of this strategy for running on slippery terrain with a simulation of a one-legged hopping robot and found that the robot was able to run up steeper and more slippery inclines using this strategy.

Dynamic Bipedal Robots

The simulated robot used in this paper is based on a planar biped robot that was constructed by Raibert and his colleagues (Raibert 1986; Hodgins, Koechling, and Raibert 1986). The simulation of the biped is three-dimensional and has three controlled degrees of freedom at each hip and one for each leg (Figure 1). In the physical robot, the leg contains a hydraulic actuator in series with an air spring. The simulation models the leg spring as a linear spring. In experiments with the physical robots, hydraulic fluid leaks created slippery spots which caused the robot to fall, as illustrated in Figures 2 and 3. This data was collected at Raibert's laboratory at the Massachusetts Institute of Technology.

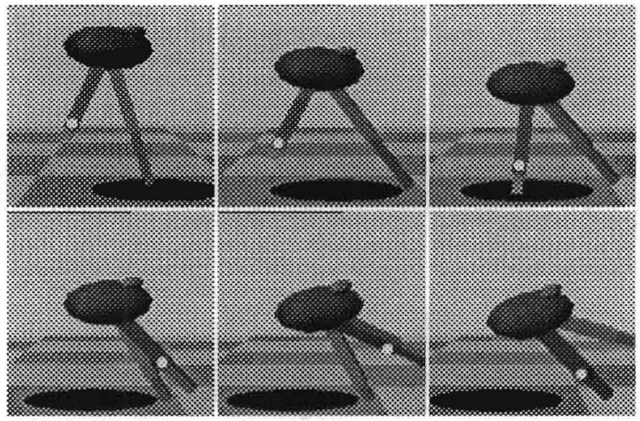

Figure 4: **Simulated Biped Slip.** The dark circle is a region with a reduced coefficient of friction. Without slipping reflexes, the biped is unable to complete a step on a slippery surface. The first leg slips, almost immediately becoming airborne as it accelerates forward. As the body falls, the second leg hits the surface, and also slips. The second legs continues to accelerate forward. [Friction coefficient: 0.04. Timestamps (s): 2.78, 2.84, 2.88, 2.90, 2.91, 2.93]

The simulation includes the equations of motion, a control system for bipedal running, a graphical model of the robot, and an user interface for interacting with the simulation. The equations of motion for the robot were generated using a commercially available package (Rosenthal and Sherman 1986). The package generates subroutines for the equations using a variant of Kane's method and a symbolic simplification phase. The parameters of the simulated robot are based on the physical robot and are listed in table 1 and table 2. A sequence of frames of a slipping simulated biped is shown in Figure 4. Data for a sequence similar to Figure 3 is plotted for the simulated biped in Figure 5.

Biped Control

Dynamically stable, steady-state running is achieved by decomposing the control problem into three largely decoupled subtasks: hopping height, forward velocity, and attitude adjustment. Hopping height is maintained by adding enough energy to the spring in the leg during stance to account for the system's dissipative losses. Forward velocity is maintained by choosing a footfall location that provides symmetric deceleration

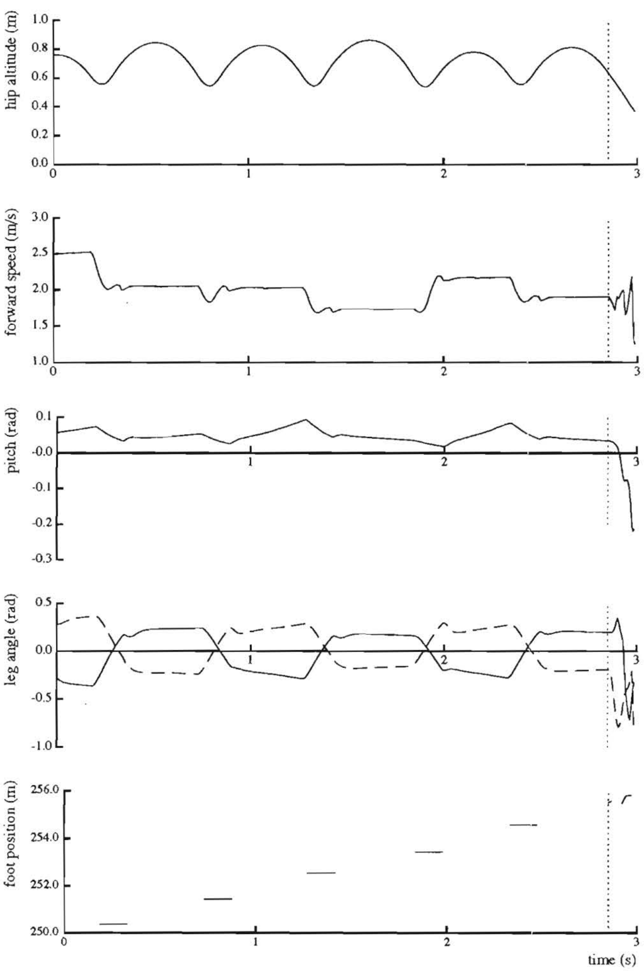

Figure 5: **Slipping Data of the Simulated Robot.** These graphs plot running and slipping for a simulated three dimensional biped. After taking five steps on a surface with a friction coefficient of 1.0, the robot steps on a region with a coefficient of 0.20 and slips. Because no slipping recovery strategies are active, the robot falls. The top three graphs show the orientation and forward speed of the body. The bottom two graphs show the leg angles of both legs and the position of each foot on the ground. When the foot slips (dotted line), it leaves the ground and the other foot soon impacts. At the start of each step, the body decelerates, then accelerates. When the slip occurs, the forward speed plot shows the body deceleration and acceleration as both feet hit the ground.

and acceleration as the leg swings through compression and decompression while the foot is on the ground. The attitude of the body (pitch, roll, and yaw) is maintained with proportional-derivative servos that apply torques between the body and the leg while the foot is on the ground. For further details on the control system, see Hodgins, Koechling, and Raibert (1986) and Raibert (1986).

The biped control system is implemented as a state machine that sequences through flight and stance phases for each leg, applying the control laws that are appropriate for each state. As shown in Figure 6, *flight* is followed by a stance phase consisting of four states. During *loading*, the foot makes contact with the ground and begins to bear the weight of the robot. During *compression*, the leg spring is compressed by the downward velocity of the robot. After the spring has stopped the vertical deceleration of the body, the body begins to rebound during *thrust*. As the leg reaches maximum extension during *unloading*, it ceases to bear any weight. After liftoff, the roles of the legs are reversed and the second leg is positioned forward in anticipation of touchdown.

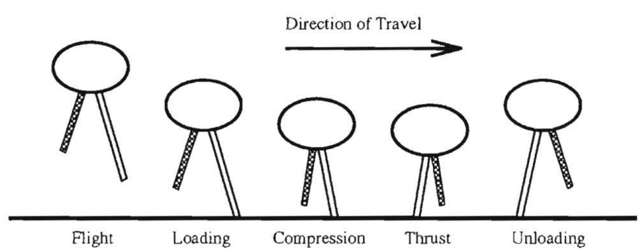

Figure 6: **Control States.** Running is achieved by dividing the step into several phases and applying the appropriate control laws during each phase. In bipedal running the legs are used in alternation so the states drawn here are repeated during the next step with the roles of the left and right legs reversed.

Slipping

The impact of the foot on the ground, the weight of the robot and the forces and torques generated in the hip and leg servos create a force on the ground during a step, as shown in Figure 7. Slipping occurs when the horizontal component of the force of the foot on the ground, F_h, exceeds the maximum force of static friction returned by the ground. A simple model of this interaction is that the maximum force of static friction is directly proportional to the normal force of the ground on the foot, F_v. Under this model, slipping will occur when the horizontal component of F exceeds the vertical component times the coefficient of static friction:

$$F_h > \mu_s F_v, \qquad (1)$$

where μ_s is the coefficient of static friction. Once slipping occurs, the horizontal force returned by the ground is given by

$$F_h = \mu_d F_v, \qquad (2)$$

where μ_d is the coefficient of dynamic friction. These relationships define a *friction cone*, illustrated in Figure 7. When the force of the foot on the ground lies within the friction cone the foot does not slip. The angle of the cone is given by

$$\theta = \tan^{-1} \mu_s. \qquad (3)$$

Note that this cone is defined for foot forces, not leg angles. The motion of the leg prior to impact affects the direction of the foot's force on the ground, as do the control torques applied to the hip joint. Leg spring forces, however, are axial to the leg. Foot forces are most likely to exceed the friction cone at the start or end of a step, where the leg angles are greatest. Slips at the start of the step are more likely because the foot is moving with respect to the ground. Slips during liftoff are are less likely since the foot is stationary. Slips during liftoff are less critical because the step is nearly complete; the controller has already executed corrections during the step. The goal in slip recovery is to move the leg so that the forces on the foot are within the friction cone.

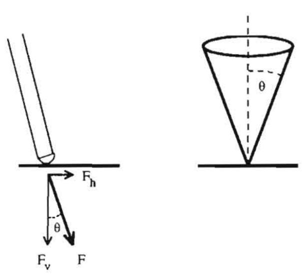

Figure 7: **Foot Forces and the Friction Cone.** During a step, the foot produces forces on the ground, F, with horizontal and vertical components, F_h and F_v. Slipping occurs when the angle of the impact force is outside the cone of friction.

Our simulations assumed minimal sensory information: nothing was known about the surface a priori and the extent of the slipping area was unavailable to the control system. This lack of sensory information limited the strategies that were available to the control system; for example, it could not prepare for a step on a slippery surface in advance of the touchdown. It could not attempt to position the foot outside the slippery area to find a good foothold. Neither the forces on the feet, nor the coefficients of friction, were available to the control system.

The control system could detect that a slip had occurred. There are several methods a physical robot could use to detect slips. Indirect methods measure joint angles and velocities or structural forces to infer slipping. Direct methods include encoder wheels and microslip detectors. For, example, a single channel encoding wheel attached to the foot could be used to detect movement of the foot during stance.

Once the control system has detected a slip, it can attempt to continue the step or it can abandon that step and pull the leg off the ground. In the first case, hip torques or leg forces can be applied to increase the vertical component of the foot force while decreasing the horizontal component, thus returning the force vector to within the friction cone. If the step is abandoned, one of the legs can be positioned during the next flight phase so that the leg angle at the next touchdown will be near vertical or both legs can be moved to a triangular configuration. In the simulations described here, we defined a recovery to be successful if the robot is able to continue running beyond the slippery region, taking subsequent steps on a non-slippery surface. Changes in velocity or hopping height were not considered to be a failure provided that the control system was able to maintain balance and return to steady-state running.

Slipping Strategies

Reacting to a slip requires careful management of the horizontal and vertical components of the forces generated by the impact of the foot on the ground. These forces vary with hopping height, forward velocity, leg angle at touchdown and velocity of the foot with respect to the ground at touchdown. Initial responses to a slip can attempt to directly alter the force vector by generating a torque at the hip or a force axial to the leg (Figure 8).

The first strategy we considered responds to a slip detection by increasing the hip torque. After the foot regains a foothold, the hip controller reverts to its normal task during a step, correcting pitch errors. The second strategy responds to a slip by compressing the leg spring to increase the force at the foot and regain a foothold. The third strategy combines these approaches.

Under some conditions, these strategies for slip re-

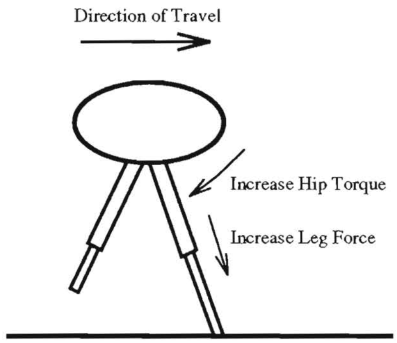

Figure 8: **Same Step Reactions.** Once a slip has been detected, the hip can be rotated or the leg can be extended to increase the vertical force on the ground.

covery have undesirable consequences. For example, a torque applied at the hip will also increase the forward velocity of the body. A decrease is preferred because the body trajectories are closer to vertical for the same hopping height. The forward velocity also determines the the leg angle at the next touchdown; slower velocities create angles that are closer to vertical. A reduced velocity therefore reduces the likelihood of a slip on a subsequent step. Applying a torque at the hip also interferes with the correction of body attitude during stance and tends to increase the pitch of the body.

Forcing the foot into the ground by increasing the desired leg length after ground contact does not interfere with body attitude adjustment and tends to slow the robot. In normal running, the leg is closer to vertical than horizontal at touchdown, so increasing the force in the leg can be expected to increase the vertical component of the force more than the horizontal component. Increasing the axial force in the leg will also add energy into the system and will increase length of the subsequent flight phase if no other control actions are taken. Although higher hops, for a given forward velocity, have more nearly vertical impacts, pitch, roll, and yaw errors can only be corrected while the robot is on the ground; higher hops allow greater accumulation of takeoff errors. To return to the desired hopping height, the added energy is removed.

The basis of the leg forcing strategy is a fundamental mechanism for gaining a firm foothold. This mechanism will be used in the other reaction strategies and discussed further in the next section.

Increasing the Foot Forces

In a normal running step, the leg spring stores energy during the stance phase and causes the body mass to have approximately equal and opposite vertical velocities at liftoff and touchdown. To maintain the duration of flight, the control system lengthens the leg to add energy equivalent to that lost due to internal mechanical losses and due to the impact of the unsprung mass of the lower leg with the ground. Thrust occurs at the moment of maximum compression of the spring, as illustrated in Figure 9. If the robot requires a higher jump and a longer flight duration, the control system extends the leg more during stance, adding more energy into the system. Reducing or eliminating the leg extension decreases the duration of the subsequent flight phase. To reduce the flight duration further, the control system can remove energy from the system by lengthening the leg spring.

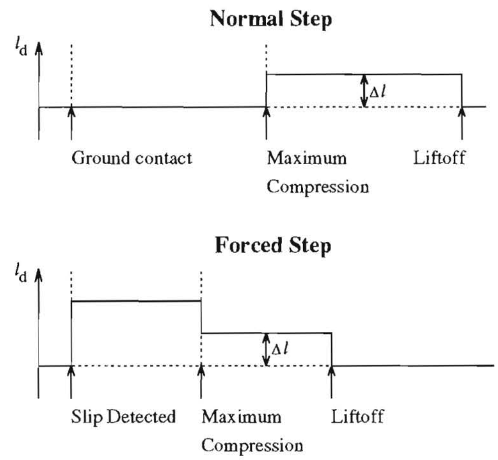

Figure 9: **Forcing the Foot into the Ground.** In a normal step, energy is added into the leg spring at the moment of maximum compression. Increasing the loading on the leg just after touchdown forces the foot into the ground but adds energy to the system. The control system must remove this energy from the spring if the flight duration is to remain constant. l_d is the desired leg length. Δl is the change in desired leg length that returns the biped to the desired hopping height.

In responding to a slip, the control system may alter this sequence by extending the leg as soon as the slip is detected. The repositioning strategies described below extend the leg immediately after touchdown and later removes the added energy by lengthening the leg spring when the leg is vertical and the danger of slipping is reduced, as illustrated in Figure 9. Because the extra energy is removed, the hopping height remains the same. The result is larger vertical foot forces on the ground soon after contact. We refer to this technique as *forcing* the foot.

A secondary effect of this strategy is that the period of time during which the spring is passively compression is reduced. As a result, the stance phase is shorter. We have observed that this quick stepping style is a useful method for briefly running on slippery surfaces because the leg angle at touchdown is near vertical. However, the shorter stance phase also reduces the time available for correction of the body attitude, making steady-state running difficult to achieve.

Reconfiguration Strategies

The step on which the initial slip occured may be abandoned by immediately lifting the foot; the resulting flight phase provides a brief opportunity to prepare for another landing on the slippery surface. By reconfiguring the legs in anticipation of a slippery surface, the control system can attempt to keep the foot forces within the friction cone. Because the coefficient of friction is not known, the size of the friction cone is unknown. Therefore the best place for the foot at the next touchdown is directly under the body, making the leg vertical at touchdown. During the step, normal pitch, roll, and yaw control are applied. Figure 10 diagrams the strategies that reposition the legs. Sequences of frames showing the single leg repositioning strategies recovering from slips are shown in Figures 11 and 12.

After a slip has been detected, both legs may be used in the recovery by configuring them in a narrow fixed triangle vertically centered under the body. The control system attempts to form and hold this triangle throughout the subsequent step and does not apply the normal pitch, roll, and yaw adjustments. Instead, the robot essentially bounces, letting the geometric configuration provide stability instead of active pitch, roll, and yaw control. This strategy assumes stable running prior to the slipping step. Note that the leg angles in normal running are nearly symmetric during the flight phase of steady-state running. The control system only has to make the leg lengths equal to create a symmetric triangle. Because the extent of the friction cone is unknown, however, the triangle is narrowed so the legs are closer vertical. Once both feet contact the ground, the leg forcing function is applied. After both feet have lifted off the ground, the control returns to a normal flight state. A sequence of frames from a slip recovery using the stable triangle strategy is shown in Figure 13.

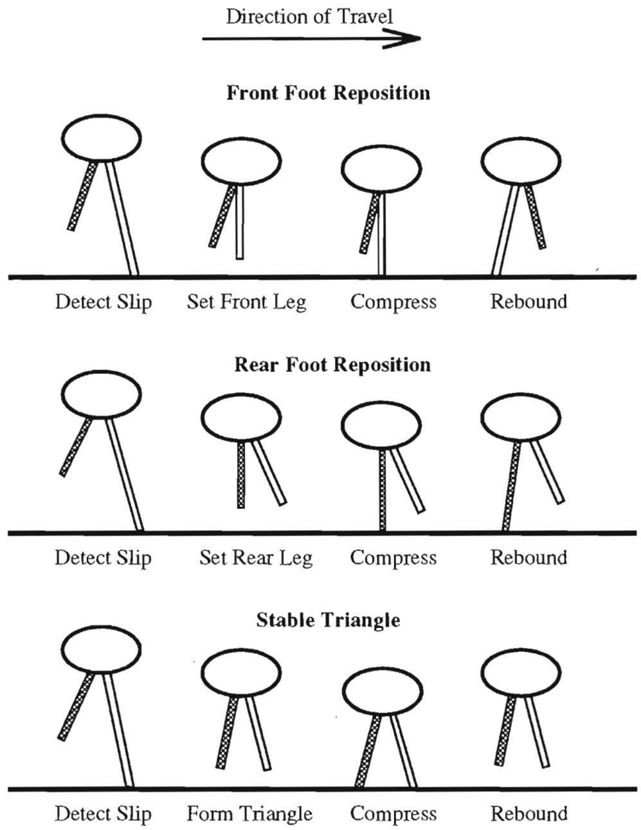

Figure 10: **Reconfiguration Strategies.** After a slip has been detected, the initial step is abandoned and one or both of the legs is repositioned for the next step. The leg angle at touchdown on the next step will be closer to vertical, keeping the impact force vector within the friction cone.

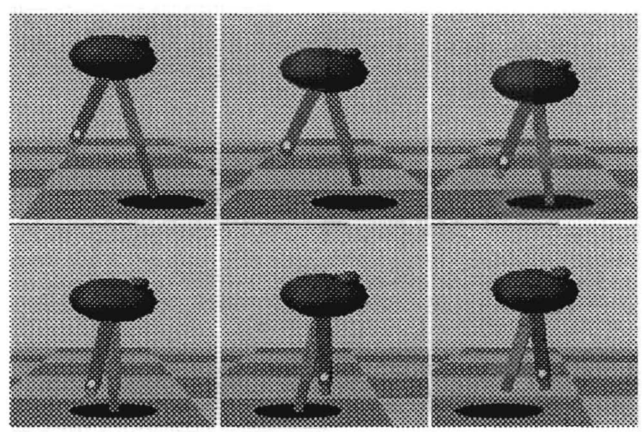

Figure 11: **Front Leg Repositioning.** The front leg is lifted and repositioned for a more vertical impact. [Friction coefficient: 0.20. Timestamps (s): 2.78, 2.81, 2.87, 2.70, 2.91, 2.93]

Simulation Results

The strategies were tested by varying the initial velocity and the coefficient of friction to produce multiple runs. A starting state was created using the configuration of the robot in mid-flight during steady-state

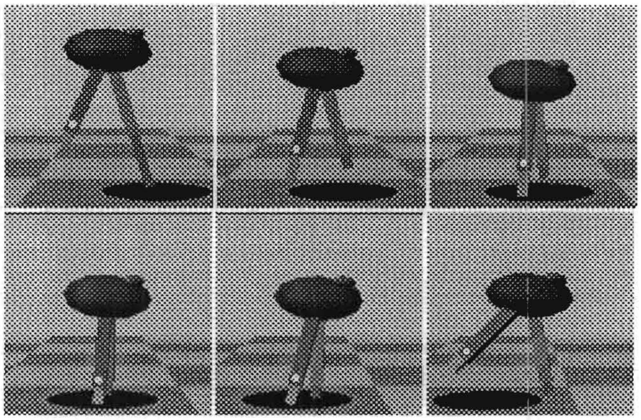

Figure 12: **Rear Leg Repositioning.** The rear leg is brought under the slipping robot to arrest the fall. Note that the newly planted leg slips upon takeoff, but the step is successful because the body attitude is not disturbed significantly. [Friction coefficient: 0.20. Timestamps (s): 2.78, 2.83, 2.85, 2.88, 2.90, 2.93]

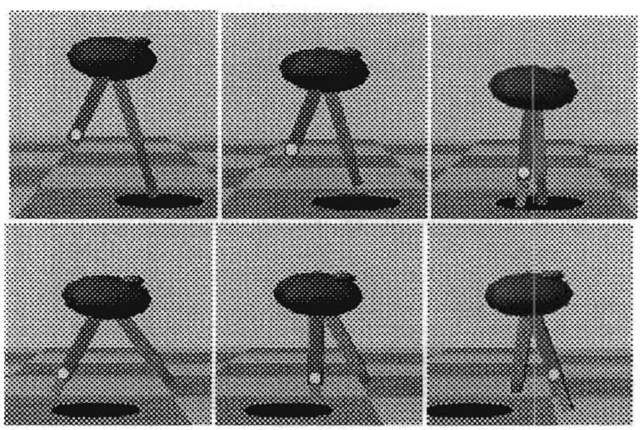

Figure 13: **Stable Triangle Recovery.** The biped forms a stable triangle. Although the legs still slip just prior to liftoff, the control system is able to recover because the slip is symmetric and occurs at the end of the step.[Friction coefficient: 0.04. Timestamps (s): 2.78, 2.81, 2.85, 2.89, 2.91, 2.97]

running. A small, circular slippery area was simulated at the location of the next footfall. During each successful run, the robot stepped once in the slippery area, and then made three additional steps on the non-slippery surface. The initial velocity was 2.5 ± 0.25 m/s. The size of the slippery area was chosen for each reaction strategy to be large enough to prevent a foot from sliding to the edge, which often allowed an easy recovery. The slippery area was small enough that subsequent footfalls were located outside the slippery area. Twenty friction coefficients between 0.05 and 1.0 were used. Both static and kinetic coefficients were set to the same value for each trial, which consisted of five simulations with different initial velocities. The robot was judged able to recover from a slip at a given coefficient of friction if three or more of trials were completed without crashing.

Figure 14 shows the range of coefficients for which each strategy could recover. Slipping did not occur until the coefficients fell below 0.95. Once slipping occurred, the normal running controller was unable to continue. The leg force and the hip torque reactions were successful down to coefficients of friction of 0.40 when the strategies were used individually and 0.45 when the strategies were combined.

For the successful trials, we computed a measure of the error at the moment of footfall of the step after the slip. The error measure was the summed absolute values of differences between the actual and desired angle for the fore-aft angle of the two legs, the pitch angle, and the roll angle:

$$\begin{aligned}\text{Error} &= |\text{hip\_}\theta_1 - \text{hip\_}\theta_{1d}| + |\text{hip\_}\theta_2 - \text{hip\_}\theta_{2d}| \\ &\quad + |\text{pitch} - \text{pitch}_d| + |\text{roll} - \text{roll}_d|\end{aligned}$$

The error calculation was designed to measure how well the slip recovery strategy had positioned the robot after the slip step, the recovery step, and the subsequent ballistic flight. The errors for the successful trials were averaged to compute the data shown in Figure 15. This graph illustrates the tradeoff between the two classes of strategies. Longer lines indicate strategies that successfully negotiate lower friction coefficients. Lower lines indicate strategies that produce lower errors.

The leg force and hip torque strategies feature smooth recoveries because they continue the slipping step and correct the previously accumulated errors. The repositioning strategies, in contrast, delay error correction and accumulate more errors due the slip and the flight phase during which the legs are reconfigured. The single leg repositioning strategies correct errors once the foot has landed on the step following the initial step. The stable triangle strategy attempts no error correction. The leg force and hip torque strategies actually show decreased errors as the coefficient of friction is lowered.

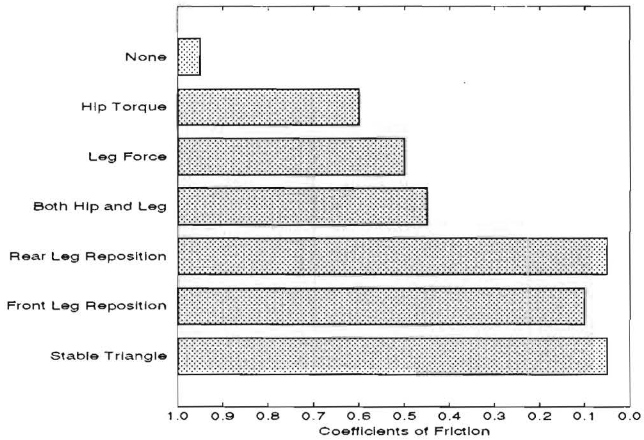

Figure 14: **Minimum Frictions.** Each strategy has a minimum friction below which it cannot recover. For recovering from a single slippery step, the leg repositioning strategies can accommodate the largest range of friction coefficients.

The repositioning strategies are successful at lower coefficients of friction than the leg force and hip torque strategies. However, the repositioning strategies cause greater errors in the subsequent steps. This tradeoff suggests that if friction coefficient estimates were available or known a priori, they could be used to select the appropriate strategy for slipping.

The rear leg repositioning strategy begins to fail at a friction coefficient of 0.40, as shown by the steep curve in Figure 15. Near this value, the strategy cannot prevent slips; errors accumulate rapidly and the number of successful recoveries declines. The front leg repositioning strategy begins to fail at 0.20. The difference is due to ground speed matching. Because the robot is moving forward while the foot is airborne, bringing the rear leg forward increases the speed difference between the foot and the ground. Bringing the front leg back reduces the speed differential. On impact, the foot with the lower differential is subjected to smaller horizontal forces and is less likely to slip.

The stable triangle strategy attempts to form a narrow triangle during the brief flight. For the speed and hopping heights used in the simulation, there was insufficient time to achieve the new configuration. As a result, the legs were moving upon ground contact and experienced both increased and decreased ground speed differentials. However, if the foot with the lower differential makes a non-slipping ground contact, the robot's speed decreases, as shown in Figure 5. The speed decrease enables the other foot to make a successful ground-contact. The stable triangle strategy begins to fail at coefficients of 0.20, like the front leg repositioning strategy.

Both the front leg repositioning and the stable triangle strategies are able to recover from slips on ground with coefficients as low as 0.05. Both experience increased slipping, but often successfully recover because the slips occur at the end of the recovery step. Figure 12 shows a successful ground contact and rebound followed by a slip upon takeoff. Because the hopping height, forward speed, and body attitude control algorithms have already been applied, the slip has little effect on the robot. Figure 13 shows slips after recovery by the stable triangle strategy. Note that the slips are nearly symmetrical. The resulting torques on the body cancel, enabling recovery with lower errors than those of slightly higher friction coefficients.

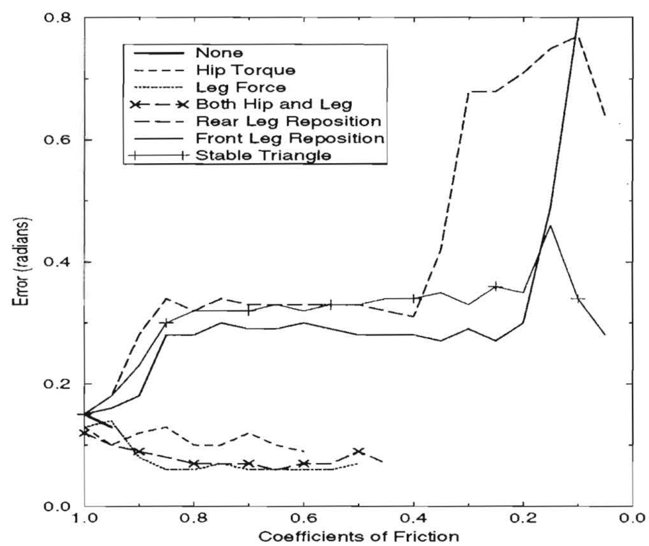

Figure 15: **Touchdown Errors.** If the robot recovers from a slip, it starts the next step with some error. This graph illustrates the tradeoff between smooth running and successful slip recovery. Lower curves indicate fewer body and leg angle errors. Longer curves indicate a greater range of friction coefficients that can be tolerated. Although the leg reposition and stable triangle strategies can recover from slips at lower coefficients of friction, they do so with increased errors.

Discussion and Conclusions

We have considered the problem of creating reflexive responses to slipping given only the detection of a presently occurring slip. We distinguished two classes of reactions, one-step strategies and two step strategies, depending on whether the correction was applied in the slip step or in the following step. Reactions that continue the slipping step produce smoother recoveries but only for the upper range of friction coefficients. Reactions that abandon the slipping step are capable of negotiating a larger range of surfaces but with larger resulting errors. Knowledge of the environment is required to choose the best strategy.

Given slipping reflexes, the extent of the slippery surface can be considered. Our simulations focussed on traversal of a single patch in which one footfall slipped. Some observations can be made regarding running on a slippery surface. For higher coefficients of friction, the strategies with the lowest errors, the force and torque reactions, are most likely to succeed. It may appear that the repositioning strategies are limited because continual slipping would cause them to abandon every other step. However, all of the reflexive the strategies reduce the forward velocity during the slip recovery, making the legs more vertical. Preliminary results indicate that only a few slipping reactions may be required to achieve steady non-slipping running on the slippery surface.

If the biped's foot is moving with respect to the ground at touchdown, the horizontal force on the ground is increased in the direction of motion, increasing the danger of slipping. Strategies for running on slippery surfaces should try to reduce the relative motion of the foot and the ground prior to impact. This principle, called *ground-speed matching*, is useful in slip prevention. It also reduces the jarring of non-slip impacts and is used by animals and human runners.

Even with models or sensors to provide knowledge of the surface properties before contact, reflexive slipping strategies are required to provide robustness under estimation error or sensor noise. Slipping reactions are also fundamental to many other rough terrain problems. Slopes, uneven surfaces, and small obstacles create oblique impact angles that can cause slipping. Reflexive slipping responses enable successful traversal of these terrains. A successful rough terrain robot will combine slipping reflexes with other walking or running primitives including reflexive strategies for stumbling, sticking, slopes, surface steps, and step-length adjustment.

Acknowledgments

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#2

Reflexive Responses to Slipping and Tripping for Bipedal Robots

Gary N. Boone and Jessica K. Hodgins

Abstract— **Many robot applications require traversing rough or unmodeled terrain. This paper explores strategies for responding to two common types of surface contact error: slips and trips. Due to the rapid response required and the inaccuracies of sensing uneven terrain, we propose a set of reflexes that respond without attempting to model or analyze the error condition. These reflexive responses enable robust recovery from a variety of contact errors. We present experimental trials for single-slip tasks with varying coefficients of friction and single-trip tasks with varying obstacle heights.**

Keywords— **reactive control, reflexes, rough terrain, slipping, tripping, biped locomotion**

I. Introduction

ROUGH terrain occurs not only in natural environments but also in environments that have been constructed or modified for human use. Currently, most legged robots lack the control techniques that would allow them to behave robustly on such relatively simple rough terrain as stairs, curbs, grass, and slopes. Even smooth topographies become difficult to traverse if they include small obstacles, loose particles, and slippery areas. Many control systems for bipedal robots have assumed steady-state running over smooth surfaces, but some have explored control techniques for rough terrain. Controllers for statically stable robots have used foot-placement algorithms to insure viable footholds. However, for dynamically stable robots, narrow timing and foot-placement requirements increase the difficulty of designing controllers than can anticipate or react to rough terrain contact errors. This paper demonstrates the utility of preprogrammed high-level responses to errors during locomotion in a complex dynamic environment. A suite of responses allows a simulated, three-dimensional, bipedal robot to recover from slipping on low friction surfaces and tripping over small obstacles. These reflexes are shown to provide robust recoveries to errors in several tasks.

Many ground contact errors would be avoided if the control system could guide the robot around slippery areas and obstacles. However, sensing the surface properties of terrain before making contact is not always possible because of the limitations of available sensors and because of the approximate nature of information obtained at a distance. Holes, steps, bumps, debris, and sticky or slippery areas are difficult to detect from a distance with current technology. If the robot cannot detect and avoid or prepare for surface features in advance, then robust locomotion on rough terrain requires that the robot respond to unexpected features after the contact error has occured. For dynamically stable robots, which run with a ballistic flight phase, these responses must be effected before the robot crashes. Thus the time available for modeling the surface and planning an appropriate reaction is severely limited. In the case of the dynamically stable biped described below, the controller may have less than a dozen controller time steps in which to choose an appropriate recovery action.

We define *reflexes* as responses with limited sensing and no modeling. That is, the robot can detect a slip, but does not attempt to estimate the surface or obstacle properties or calculate a corresponding recovery plan. Instead, the slipping and tripping sensors trigger fixed responses. These reflexes are defined at a high level, such as reconfigurations of the leg positions, and at a low level, such as the modification of servo gains. Just as animal motor programs can be considered both open-loop and closed-loop[1], sev-

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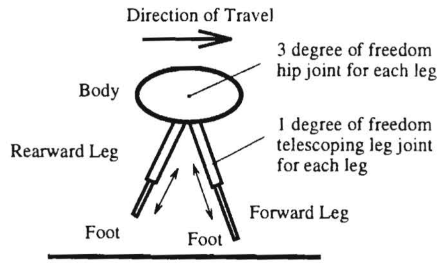

Fig. 1. **Biped Structure.** The simulated bipedal robot consists of a body and two telescoping legs. Each leg has three degrees of freedom at the hip and a fourth degree of freedom for the length of the leg.

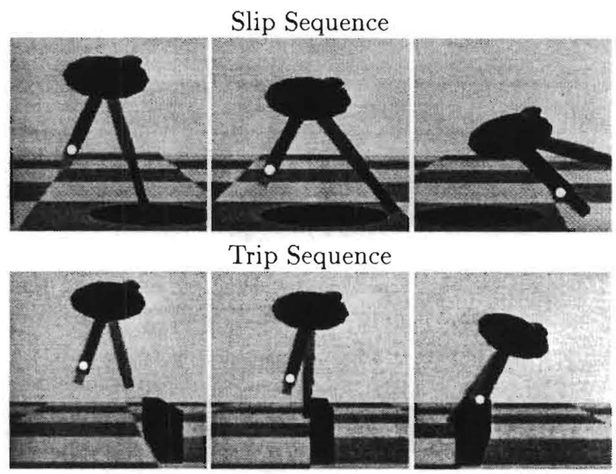

Fig. 2. **Examples of a Slip and Trip.** Without controller enhancements, the simulated robot does not respond to slippery areas or obstacle contacts, leading to crashes.

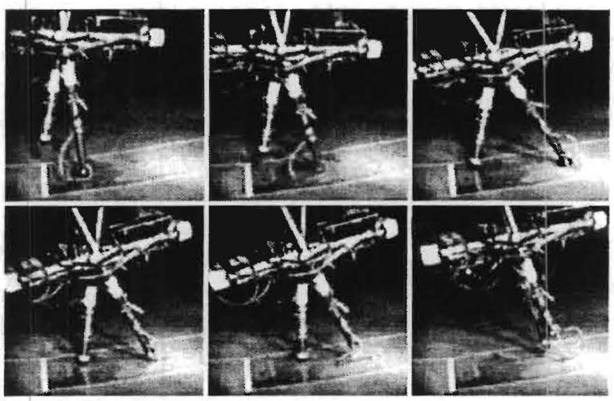

Fig. 3. **Physical Biped Slip.** Planar two-legged robot running across an oily spot on the floor of the Leg Laboratory at the Massachusetts Institute of Technology. (Timestamps (s): 0.5, 1.67, 2.83, 3.53, 4.00, 5.17)

eral low-level feedback control laws to operate during the primarily open-loop reflex responses. For example, a reflex may reconfigure the leg position, but sensing is used to determine transitions in the leg controller state machine during the recovery step.

During experimentation with a planar bipedal robot, the robot sometimes slipped on hydraulic oil or tripped on cables in its path. Because the robot had no responses customized for these error conditions, it almost always immediately crashed. This paper reports a set of fixed reflexes that were sufficient to enable robust recoveries for this complex, dynamic system in tasks involving a single slip or trip.

In the next section, we describe previous approaches to legged locomotion in rough terrain. In Section III, we consider biological reflexes. Section IV describes the simulated biped robot and its control system. The slipping problem, slipping reflexes, and simulation results are presented in Section V, followed by the tripping problem, tripping reflexes, and results in Section VI. The reflex approach and results are discussed in Section VII.

II. Rough Terrain Locomotion

A suitable foothold is one that allows a legged system to maintain balance and continue walking or running. For statically stable locomotion, the difficulty is not in placing the robot's feet on footholds, but in deciding which locations on the terrain provide suitable footholds. Successful locomotion on rough terrain has been demonstrated by the Adaptive Suspension Vehicle[2] and Ambler[3], [4], [5]. These large, statically stable machines have traversed grassy slopes, muddy cornfields, and surfaces that include railroad ties and large rocks. Static stability has allowed these robots emphasize detection at a distance and avoidance of obstacles and uncertain footholds.

Klein and Kittivatcharapong[6] proposed algorithms for ensuring that foot forces remain within the friction cone and identifying situations in which these constraints, or the desired body forces and torques, cannot be achieved. Their work addressed prevention of slipping and did not consider sensor noise or responses to unmodeled surfaces.

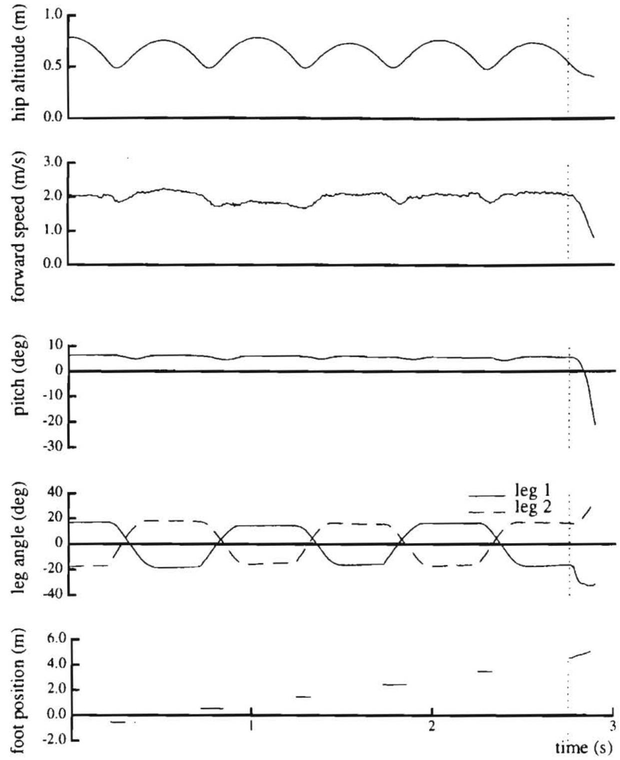

Fig. 4. **Slipping Data of the Physical Robot.** The physical planar robot slipped on oil during a laboratory experiment at the point indicated by the vertical dotted lines. The top three graphs show the height, forward speed, and orientation of the body. The bottom two graphs show the leg angles of both legs and the position of each foot on the ground. For each step but the last, the foot is stationary while it is on the ground.

For dynamically stable robots, the control of step length for locomotion on rough terrain interacts with the control of balance. Hodgins and Raibert[7] implemented three methods for controlling step length of a running biped robot. Each method adjusted one parameter of the running cycle: forward running speed, running height, or duration of ground contact. 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. However, unlike the tasks described below, the size and location of the objects were known to the controller in advance.

Nagle[8] developed algorithms for running on terrain that was known to be slippery. By running slowly, the robot generated nearly vertical foot forces. His controller used *a priori* knowledge or estimation of friction coefficients to prevent slipping by confining control forces and torques to slip-free regions.

III. Reflexive Responses to Errors

Biological systems use many different reflexes in locomotion and manipulation. Reflexes help to restore balance when perturbations occur during walking or standing[9], [10], [11]. The role of reflexes in walking is complex: the same stimulus elicits a different response in the stance phase than in the swing phase[12], [13], [14]. Touching the foot of a cat or human during a swing phase, for example, will cause the leg to flex, raising the foot. If an obstacle caused the stimulus, this response might lift the foot over the obstacle and allow walking to continue. During the stance phase, a stimulus delivered to the foot causes the leg to push down harder, resulting in a shorter stance phase. Although these actions are opposite, both facilitate the continuation of locomotion.

Robotics has adopted the term "reflex" from the biological literature, but in both biology and robotics the precise definition of the term varies from study to study. Most researchers in robotics use the term to mean a quick response initiated by sensory input. Some require reflexes to be open-loop and to proceed independently of subsequent sensory input[15], [16]; others apply the term more loosely to describe actions that are performed with feedback until a terminating sensory event occurs[17]. In some cases, reflexes refer to general purpose actions[18], [19] and in others only to actions taken to correct errors or to compensate for disturbances[17].

Brooks's subsumption architecture[19] combined several simple reflex-like actions to produce complex behaviors such as six-legged walking. A global gait generator specified the order of leg use while inhibitory connections between the legs prevented conflicting reflexes from acting simultaneously.

Hirose[18] built and controlled a statically stable quadruped that used a reflexive probing action to climb over objects and to walk up and down steps without visual input or a map of the terrain.

Wong and Orin[17] implemented two reflex responses for a prototype leg of the Adaptive Suspension Vehicle. Using velocity and hydraulic pressure information from sensors at the joints, they were able to detect foot contact and slippage. The foot contact reflex reduced the peak forces at touchdown. The foot slippage reflex was used to detect and halt slipping.

Reflex responses have also been used in manipulation. Tomovic and Boni[15] used a reflex response to implement grasping for the Belgrade prosthetic hand. Bekey and Tomovic[16] continued the exploration of prosthetic control systems with a rule-based technique that relied on sensory data and fixed response patterns.

IV. Dynamic Bipedal Robots

The simulated robot used in our research is based on a planar biped robot constructed by Raibert and colleagues[20], [21]. The simulated biped is three-dimensional and has three controlled degrees of freedom at each hip and one for the length of each leg (Figure 1). In the physical robot, the leg contains a hydraulic actuator in series with an air spring. The simulation models the leg spring as a linear spring with a controllable rest length. In experiments with the physical robots, hydraulic fluid leaks occasionally created slippery spots that caused the robot to fall (Figures 3 and 4). A simulation of a similar fall is plotted in Figures 5 and 6. The physical robot was also

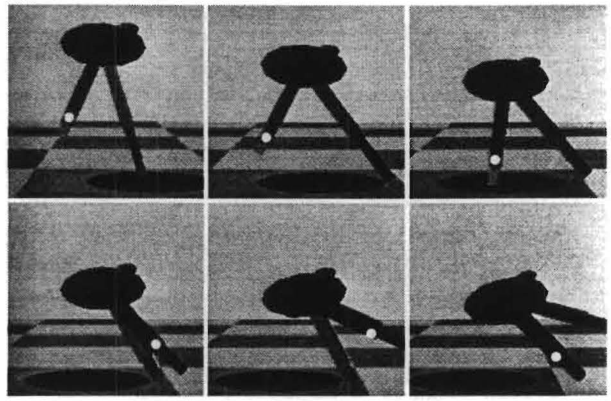

Fig. 5. **Simulated Biped Slip.** The dark circle represents an area of the floor with a reduced coefficient of friction. Without slipping reflexes, the simulated biped is unable to complete a step on a slippery surface. The first leg slips, almost immediately becoming airborne as it accelerates forward. As the body falls, the second leg hits the surface and also slips. The second leg continues to accelerate forward. [Friction coefficient: 0.04. Timestamps (s): 0.78, 0.84, 0.88, 0.90, 0.91, 0.93]

able to climb stairs and jump over boxes[21]; however, the positions of the obstacles were known in advance. The current research extends the controller to handle unexpected slips and unanticipated box impacts.

The simulation includes the equations of motion, a control system for bipedal running, a graphical model of the robot, and a user interface for interacting with the simulation. The equations of motion for the robot were generated using a commercially available package[22]. The parameters of the simulated robot are based on the physical robot.

The controller achieves dynamically stable, steady-state running by decomposing the control problem into three largely decoupled subtasks: hopping height, forward velocity, and body attitude. Hopping height is maintained by adding enough energy to the spring in the leg during stance to account for the system's dissipative losses. Forward velocity is maintained by choosing a leg angle at touchdown that provides symmetric deceleration and acceleration as the leg swings through compression and decompression while the foot contacts the ground. The attitude of the body (pitch, roll, and yaw) is maintained with proportional-derivative servos that apply torques between the body and the leg while the foot is on the ground.

The biped control system is implemented as a state machine that sequences through flight and stance phases for each leg, applying the control laws that are appropriate for each state. As shown in Figure 7, *flight* is followed by a stance phase of four states. During *loading*, the foot makes contact with the ground and begins to bear the weight of the robot. During *compression*, the leg spring is compressed by the downward velocity of the robot. After the spring has stopped the vertical deceleration of the body, the body begins to rebound during *thrust*. As the leg reaches maximum extension during *unloading*, it ceases to bear weight. After liftoff, the roles of the legs are reversed and the second leg is positioned forward in anticipation

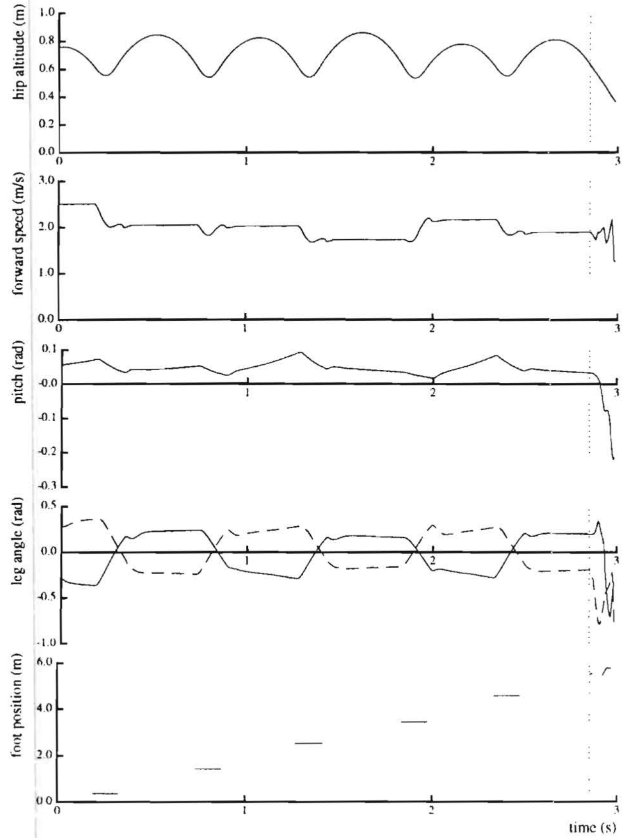

Fig. 6. **Slipping Data of the Simulated Robot.** After taking five steps on a surface with a friction coefficient of 1.0, the robot steps on a region with a coefficient of 0.20 and slips. Because no slipping recovery strategies are active, the robot falls. The top three graphs show the height, forward speed, and orientation of the body. The bottom two graphs show the leg angles of both legs and the position of each foot on the ground. When the foot slips (vertical dotted line), it leaves the ground and the other foot soon impacts.

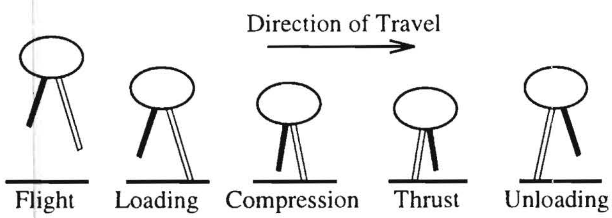

Fig. 7. **Control States.** Running is achieved by dividing each step into several phases and applying the appropriate control laws during each phase.

of touchdown. For further details on the control system, see [21] and [20].

V. Slipping

The impact of the foot on the ground, the weight of the robot, and the forces and torques generated by the hip and leg servos create a force on the ground during a step (Figure 8). Slipping occurs when the horizontal component of the force of the foot on the ground, F_h, exceeds the maximum force of static friction returned by the ground. A simple model of this interaction is that the maximum force of static friction is directly proportional to the normal force

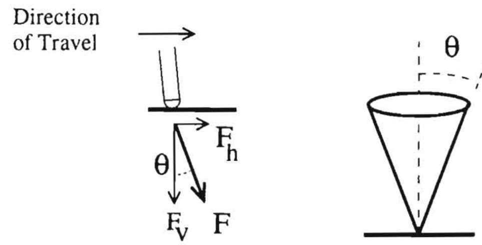

Fig. 8. **Foot Forces and the Friction Cone.** During a step, the foot produces forces on the ground, F, with horizontal and vertical components, F_h and F_v. Slipping occurs when the angle of the impact force is outside the friction cone.

of the ground on the foot, F_v. Under this model, slipping will occur when the horizontal component of F exceeds the vertical component times the coefficient of static friction:

$$F_h > \mu_s F_v,$$

where μ_s is the coefficient of static friction. When slipping occurs, the horizontal force returned by the ground is given by

$$F_h = \mu_d F_v,$$

where μ_d is the coefficient of dynamic friction. These relationships define a *friction cone*, illustrated in Figure 8. When the force of the foot on the ground lies within the friction cone, the foot does not slip. The angle of the cone is given by

$$\theta = \tan^{-1} \mu_s.$$

Note that this cone is defined for foot forces, not leg angles. The motion of the leg prior to impact affects the direction of the foot's force on the ground, as do the control torques applied to the hip joint and the leg spring. Foot forces are most likely to exceed the friction cone at the beginning or end of a step, when the leg angles are greatest. Slips at the beginning of a step are more likely than slips at liftoff because the foot is moving with respect to the ground at touchdown. In contrast, the foot is stationary at liftoff. Slips during liftoff are often less critical because the step is nearly complete; the controller has already executed corrections during the step.

Our simulations assumed minimal sensory information: the properties of the surface and the extent of the slipping area were not available to the control system. The controller could not adjust the leg configuration prior to touchdown or try to position the foot outside the slippery area to find a secure foothold. Neither the forces on the feet nor the coefficients of friction were available to the control system. However, the control system could detect slips. In the simulation, slips were detected when a foot moved while in contact with the ground. A physical robot can detect slips indirectly by measuring joint angles and velocities or structural forces. Direct methods include encoder wheels and microslip detectors.

Once the control system has detected a slip, it can attempt to continue the step or it can abandon that step and pull the leg off the ground. In the first case, hip torques or

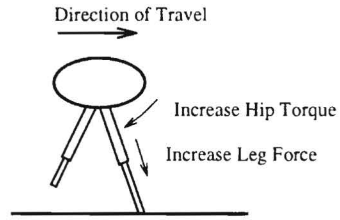

Fig. 9. **Same-Step Reactions.** Once a slip has been detected, a torque can be applied at the hip or the leg can be extended to increase the vertical force on the ground.

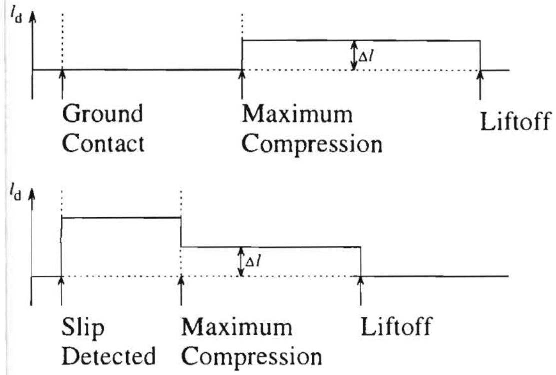

Fig. 10. **Forcing the Foot into the Ground.** In a normal step (top), energy is added into the leg spring at the moment of maximum compression. In the forced step (bottom), the loading on the leg is increased just after touchdown, forcing the foot into the ground and shortening the step duration. l_d is the desired leg length. Δl is the change in desired leg length that returns the biped to the desired hopping height.

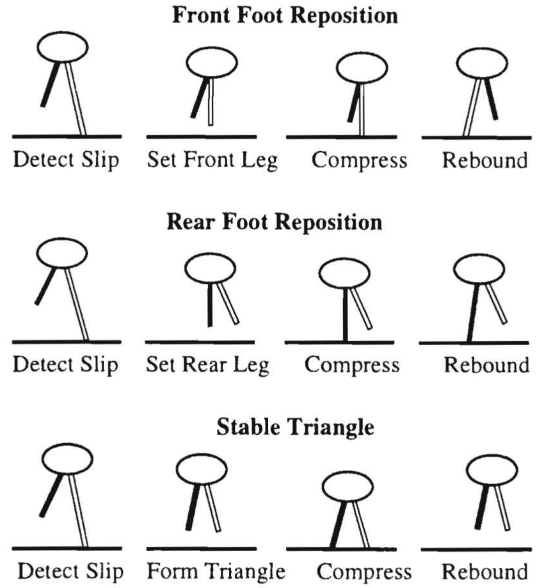

Fig. 11. **Repositioning Strategies.** After a slip has been detected, the initial step is abandoned and one or both legs are repositioned for the next step. The leg angle at touchdown on the next step will be closer to vertical, keeping the impact force vector within the friction cone.

leg forces can be applied to increase the vertical component of the foot force while decreasing the horizontal component, thus returning the force vector to within the friction cone. If the step is abandoned, one of the legs can be positioned during the next flight phase so that the leg angle at the next touchdown will be near vertical or both legs can be moved to a triangular configuration. In the simulations described here, we defined a recovery to be successful if the robot was able to continue running beyond the slippery region, taking subsequent steps on a non-slippery surface. Changes in velocity or hopping height were not considered failures provided that the control system was able to maintain balance and return to steady-state running.

A. Same-Step Response Strategies

Reacting to a slip requires careful management of the horizontal and vertical components of the forces generated by the impact of the foot on the ground. Initial responses to a slip can attempt to directly alter the force vector by generating a torque at the hip or a force axial to the leg (Figure 9).

The first reaction we considered responds to a slip by increasing the hip torque by a fixed amount. In most cases, this action increases the vertical component of the foot's force on the ground. After the foot stops slipping, the hip controller reverts to its normal task of correcting pitch errors. This strategy may have undesirable consequences because a torque applied at the hip also increases the forward velocity of the body. Thus the strategy may increase the likelihood of a slip on a subsequent step. Applying a torque at the hip also interferes with the correction of body attitude during stance and tends to increase the pitch of the body.

The second reaction responds to a slip by compressing the leg spring a fixed amount to increase the vertical force at the foot and regain a foothold. In a normal running step, the leg spring stores energy during the stance phase and causes the body mass to have approximately equal and opposite vertical velocities at liftoff and touchdown. To maintain the duration of flight, the control system lengthens the leg to add energy equivalent to that lost due to internal mechanical losses and due to the impact of the unsprung mass of the lower leg with the ground. In a normal step, thrust occurs at the moment of maximum compression of the spring (Figure 10). In responding to a slip, the control system may alter this sequence by extending the leg as soon as the slip is detected. This extension increases the vertical component of the foot's force on the ground, causing the force vector to reenter the friction cone. The extension also adds energy into the leg spring. The extra energy is removed later in the step by lengthening the leg spring when the leg is vertical, leaving the hopping height unchanged (Figure 10). The result of extending the leg is greater vertical foot forces on the ground soon after contact. Another effect of this reaction is to slow the robot, a desirable effect when the surface is slippery.

A secondary effect of this reaction is that the period of time during which the spring is passively compressed is reduced. As a result, the stance phase is shorter. We have observed that this quick-stepping behavior is a useful method for briefly running on slippery surfaces because the leg angle at touchdown is near vertical. However, the shorter stance phase also reduces the time available for correction of the body attitude, making steady-state running difficult to achieve.

B. Repositioning Strategies

The step on which the initial slip occured may be abandoned by immediately lifting the foot; the resulting flight phase provides a brief opportunity to prepare for another landing on the slippery surface. By reconfiguring the legs in anticipation of a slippery surface, the control system can attempt to keep the foot forces within the friction cone. Because the coefficient of friction is not known, the size of the friction cone is unknown. Therefore, the best place for the foot at the next touchdown is directly under the body, making the leg vertical at touchdown. Figure 11 diagrams the strategies that reposition the legs. Figure 13 contains a sequence of frames showing the rear leg repositioning strategy recovering from a slip.

After a slip has been detected, both legs may be used in the recovery by configuring them in a narrow fixed triangle vertically centered under the body. The control system attempts to hold this triangle throughout the subsequent step and does not apply the normal pitch, roll, and yaw adjustments. Instead, the robot bounces, letting the geometric configuration provide stability instead of active control. The leg angles in normal running are nearly symmetric during the flight phase of steady-state running; the control system only has to equalize the leg lengths to create a symmetric triangle. Because the extent of the friction cone is unknown, the triangle is narrowed so the legs are close to vertical. When both feet contact the ground, foot forcing is applied to each. After both feet have lifted off the ground, the control returns to a normal flight state. For low coefficients of friction, the legs may slip just prior to liftoff. However, the control system is able to recover because the slips are nearly symmetrical. The resulting torques on the body cancel, reducing the effects on the body attitude. Figure 14 contains a sequence of frames showing a slip recovery using the stable triangle strategy.

C. Slipping Results

The slipping strategies were tested by varying the initial velocity of the robot and the coefficient of friction to produce multiple runs. A circular slippery area was simulated at the location of the next footfall. During each successful run, the robot stepped once in the slippery area and then three additional times on the non-slippery surface. The initial velocity was 2.5 ± 0.25 m/s. The size of the slippery area for each reaction strategy was large enough to prevent a foot from sliding to the edge, a situation that allowed an easy recovery. The slippery area was small enough that subsequent footfalls were located outside it. Twenty friction coefficients between 0.05 and 1.0 were used. Both static and dynamic coefficients were set to the same value for each trial, which consisted of five

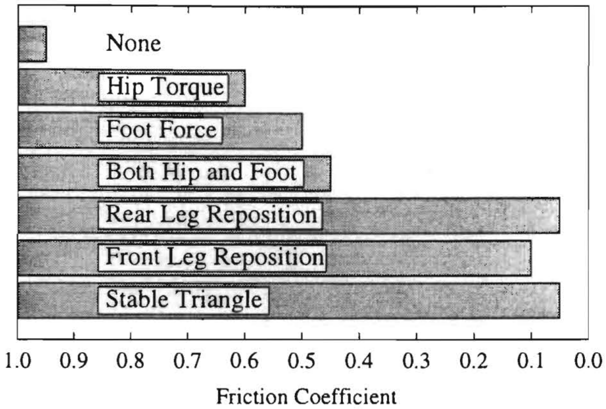

Fig. 15. **Minimum Frictions.** Each strategy has a minimum friction below which it cannot effect a recovery. The leg repositioning strategies can accommodate the largest range of friction coefficients.

simulations with different initial velocities. The robot was judged able to recover from a slip at a given coefficient of friction if three or more trials were completed successfully.

Figure 15 shows the range of coefficients for which each strategy could effect a recovery. Slipping did not occur until the coefficients fell below 0.95. After slipping occurred, the normal running controller was unable to continue. The hip torque and the foot force reactions were successful down to friction coefficients of 0.60 and 0.50 when the strategies were used individually and to 0.45 when the strategies were combined.

For the successful trials, we computed a measure of the error at touchdown of the step after the slip. The error measure was the summed absolute values of differences between the actual and desired angle for the fore-aft angle of the two legs, θ_1 and θ_2, the pitch angle, β, and the roll angle, γ:

$$\text{Error} = |\theta_1 - \theta_{1d}| + |\theta_2 - \theta_{2d}| + |\beta - \beta_d| + |\gamma - \gamma_d|$$

The error calculation was designed to measure how well the slip recovery strategy had positioned the robot after the slip step, the recovery step, and the subsequent ballistic flight. The errors for the successful trials were averaged to compute the data shown in Figure 16. This graph illustrates the tradeoff between the two types of strategies. Longer curves indicate strategies that successfully negotiate lower friction coefficients. Lower curves indicate strategies that produce reduced errors.

The foot force and hip torque strategies provide smooth recoveries because they continue the slipping step and correct the previously accumulated errors. The repositioning strategies, in contrast, delay error correction and accumulate larger errors while the legs are reconfigured. As a result, the repositioning strategies produce larger errors upon return to normal running.

The rear leg repositioning strategy begins to fail at a friction coefficient of 0.40, as shown by the steep curve in Figure 16. Near this value, the number of successful recoveries declines and the remaining recoveries accumulate

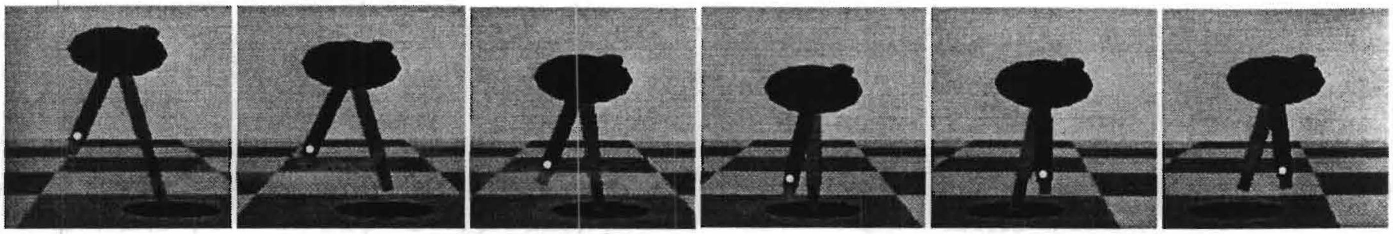

Fig. 12. **Front Leg Repositioning.** The front leg is lifted and repositioned for a more vertical impact. [Friction coefficient: 0.20. Timestamps (s): 0.78, 0.81, 0.87, 0.70, 0.91, 0.93]

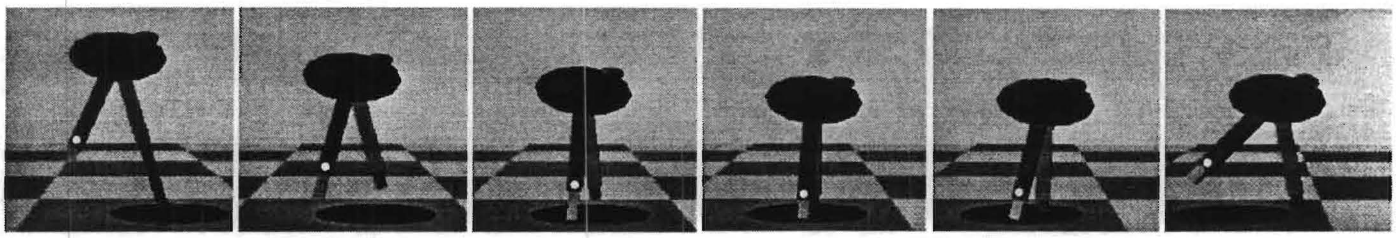

Fig. 13. **Rear Leg Repositioning.** The rear leg is brought under the slipping robot to arrest the fall. The newly planted leg slips upon takeoff, but the step is successful because the body attitude is not disturbed significantly. The robot is able to continue running. [Friction coefficient: 0.20. Time stamps (s): 0.78, 0.83, 0.85, 0.88, 0.90, 0.93]

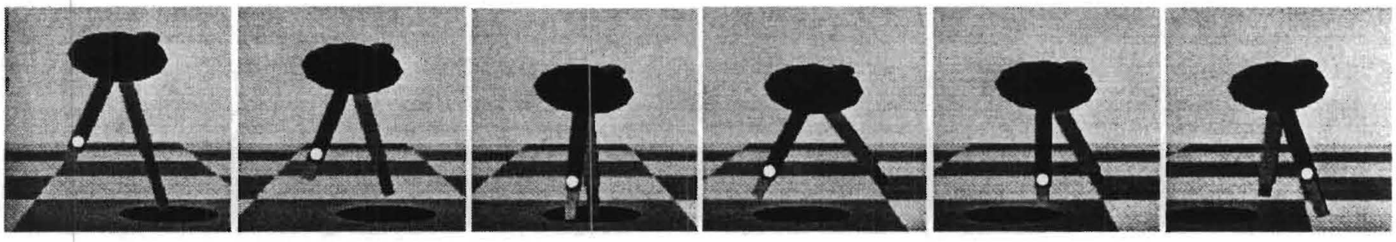

Fig. 14. **Stable Triangle Recovery.** After detecting a slip, the biped forms a stable triangle. Although the legs slip just prior to liftoff, the control system is able to recover because the slip is symmetric and occurs at the end of the step. [Friction coefficient: 0.04. Timestamps (s): 0.78, 0.81, 0.85, 0.89, 0.91, 0.97]

large errors. The front leg repositioning strategy begins to fail at 0.20. The difference between the strategies is probably due to differences in the relative speeds of the foot and the ground for each strategy. Because the robot is moving forward while the foot is airborne, bringing the rear leg forward increases the relative speed between the foot and the ground. Bringing the front leg back reduces the relative speed. On impact, the foot with the lower relative speed is subjected to smaller horizontal forces and is less likely to slip.

Both the front leg repositioning and the stable triangle strategies enable the robot to recover from slips on ground with coefficients as low as 0.05. With either strategy, the robot experiences increased slipping as the coefficient decreases, but it often successfully recovers because the slips occur at the end of the recovery step. Figure 14 shows a successful ground contact and rebound followed by a slip upon takeoff. Because the hopping height, forward speed, and body attitude control algorithms have already been applied, the slip has little effect on the robot.

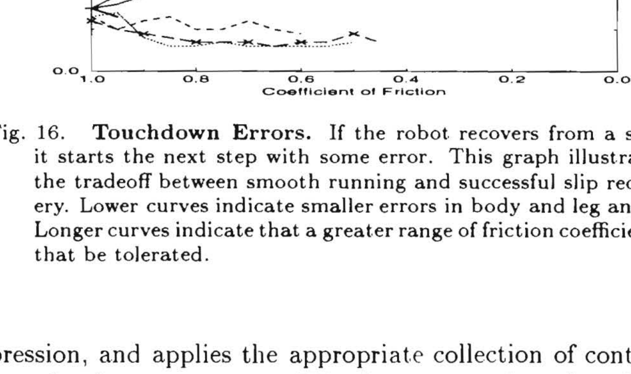

Fig. 16. **Touchdown Errors.** If the robot recovers from a slip, it starts the next step with some error. This graph illustrates the tradeoff between smooth running and successful slip recovery. Lower curves indicate smaller errors in body and leg angle. Longer curves indicate that a greater range of friction coefficients that be tolerated.

VI. Tripping

During normal running, the control system detects expected events, such as foot contact or initial leg spring compression, and applies the appropriate collection of control laws for the current state. Tripping occurs when the robot feet, legs, or body encounter unexpected obstacles, causing the controller to execute inappropriate servo commands.

To experiment with reflexive responses to tripping, we

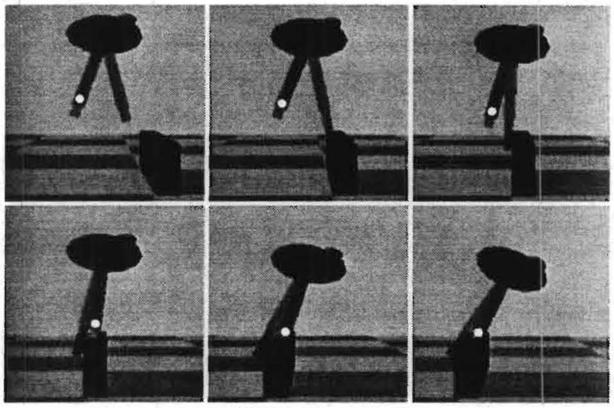

Fig. 17. **Simulated Trip.** The front foot contacts the vertical face of a box and slides down the surface. With no response, the robot is unable to continue running and crashes. Timestamps (s): 0.64, 0.69, 0.73, 0.77, 0.81, 0.84]

considered the task of returning to steady-state running after impacting an unexpected obstacle placed in the path of the robot. The existing controller was able to continue running for some unexpected contacts. For example, firm foot contacts on the top surfaces of boxes, though premature in the flight phase, generally allowed a normal and successful step to occur. Oblique contacts, such as brushing the side of the box, also did not prevent normal running from continuing. Other contacts, such as a foot or leg contacting the vertical face of a box, resulted in crashes.

A. Tripping Responses

As in the slipping case, the sensing requirements were minimal. The controller detected only that a contact with a foot or leg had occurred. It did not detect whether it was a foot contact or leg contact, nor where on the leg the contact occurred. Thus, these conditions could be determined relatively easily on a physical robot with ribbon switches on the legs or via the existing joint angle sensors.

When a leg or foot hits the front surface of a box, a foot must be repositioned to find a foothold on or beyond the box. In the case of the forward foot hitting the box, either the forward or the rear foot can be retracted and repositioned to contact the top surface of the box, where good footholds are available. We call these strategies the "front lift" and "rear lift" reflexes, depending on which leg is lifted to the top surface of the box. In the case where the rear leg hits a box, the leg can be pulled back, allowing it to pass over the box without contact using a strategy we call "rear pull." These reflexes are illustrated in Figure 18.

B. Tripping Results

To test the tripping reactions, boxes of varying heights were placed in the path of a robot running in steady state. For the front lift and rear lift reflexes, the vertical face of each box was divided into 20 impact heights and the robot was released with the front foot 2 cm from the box at each height. For the rear pull reflex, the robot was placed straddling boxes of varying heights with the forward

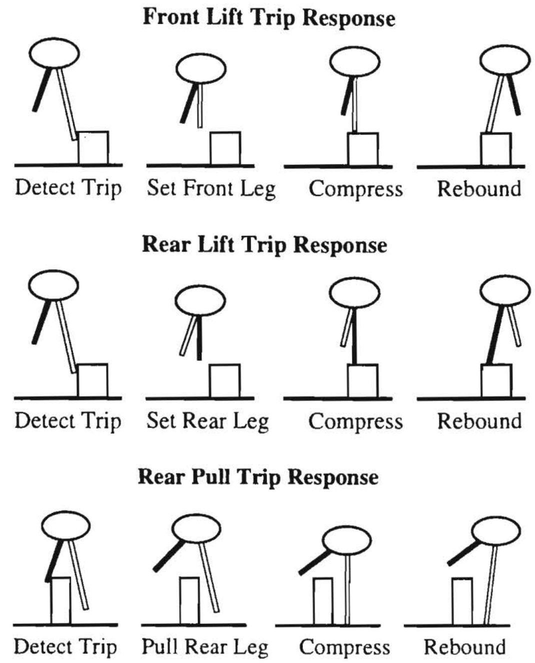

Fig. 18. **Trip Recovery Strategies.** After a trip has been detected, one of the legs is repositioned to attempt to contact the top surface of the obstacle or avoid it entirely.

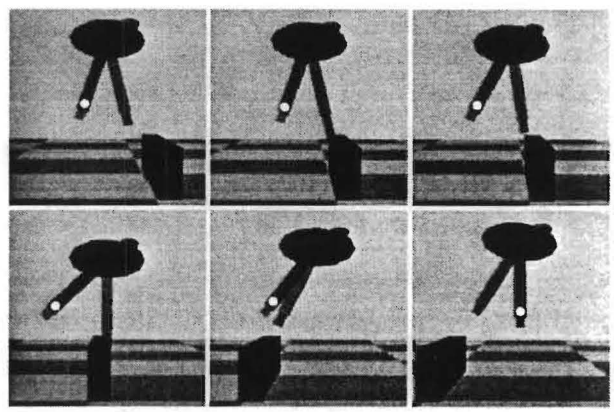

Fig. 19. **Front Lift Trip Response.** The front leg is lifted and repositioned to achieve a better foothold. [Timestamps (s): 0.64, 0.68, 0.70, 0.77, 0.87, 0.91]

foot making an initial ground contact in a normal running step. As the box height increased, the rear leg eventually contacted the box as it swung forward. In all simulations, the initial forward speed of the robot was varied by a small random factor.

For the tripping tasks, the body attitude error was used, that is the sum of the absolute values of the errors between actual and desired yaw, α, pitch, β, and roll, γ:

$$\text{Error} = |\alpha - \alpha_d| + |\beta - \beta_d| + |\gamma - \gamma_d|$$

This error measure does not include the leg angle errors because the tripping responses raise the rearmost leg to insure that it avoids the obstacle. Further, because the box impacts often caused the robot to turn, the yaw error was included in the tripping error measure.

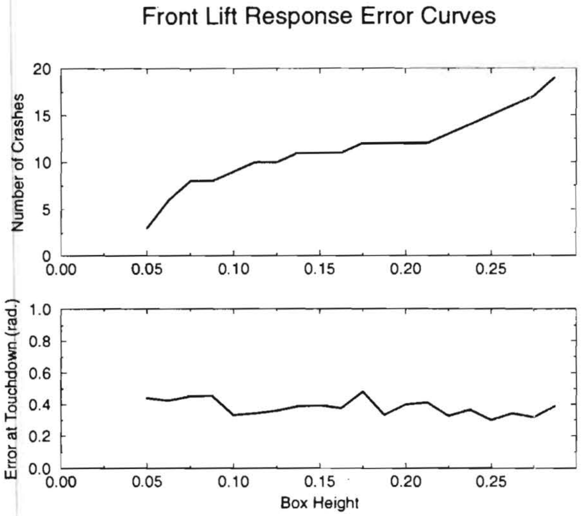

Fig. 20. **Front Lift Results.** The top graph shows the number of crashes as the obstacle height increases. The bottom graph shows the average error in body attitude at the start of the next step after recovering from a trip. As the box height increases, trips more often lead to crashes. Note however, that the errors remain relatively constant when the robot is able to recover and continue running. There were 20 runs per box height. Box heights below 5cm did not cause trips, while box heights above 28.75cm did not allow any recovery.

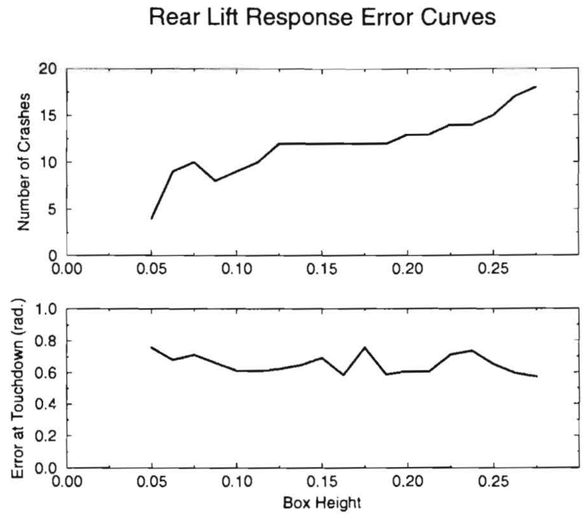

Fig. 21. **Rear Lift Results.** Taller boxes are more likely to cause a crash. However, if the robot does recover, it does so with a relatively constant error. The rear lift reflex recovers about as often as the front lift reflex (Figure 20), but with higher resulting errors. There were 20 runs per box height.

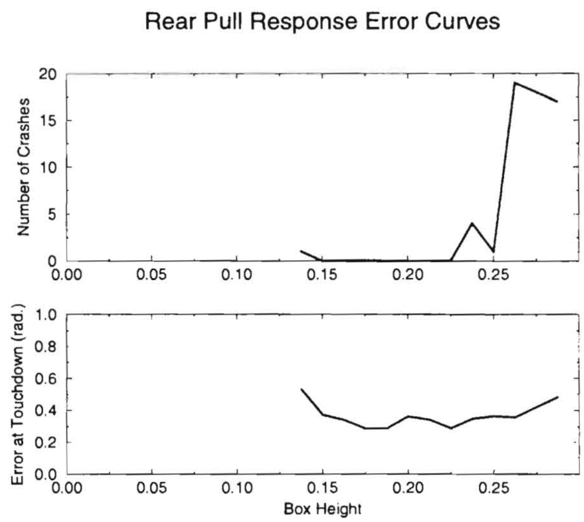

Fig. 22. **Rear Foot Pull Results.** Pulling the tripping foot back so it passes over the box allows the robot to continue running, but with some additional attitude error. For box heights below 13.75cm, the rear foot passes over the box without tripping due to the retraction of the leg during running. There were 20 runs per box height with variation in the robots initial velocity.

With no reflex responses, the robot was unable to continue running following a trip. The lifting response curves show that as the box heights increase, the tripping reflexes are less likely to produce a successful recovery (Figures 20 and 21). The number of crashes increases as the box height increases. This increase in crashes is due to the increasing distances to the box top as the height increases. If the foot hits the box near the top, there may be sufficient time to lift it to the top of the box. However, as the box height increases, fewer potential impact points are near the top edge of the box. The bottom graphs in Figures 20 and 21 show that if the robot is able to recover, it does so with approximately the same error independent of box height.

The front lift reflex causes less error than does the rear lift reflex. The front foot only has to lift over the box edge, whereas the rear foot must travel from behind the robot to the box. Therefore the rear lift reflex accumulates more errors during the additional flight time.

With no reflex responses, the robot is unable to recover when the rear leg hits a box of any height. However, Figure 22 shows that pulling the leg back after the initial contact allows the robot to pass the leg over 23 cm boxes, causing no crashes. For higher boxes, the leg, though pulled back, hits the box again, but may still be able to recover without increasing the attitude error. Above 25cm, the boxes are too high for the retracted leg to pass over, leading to a large increase in the number of crashes.

VII. Discussion and Conclusions

We have considered the problem of creating reflexive responses to slipping and tripping given only the detection of the event after it has occurred. For slipping, we evaluated two kinds of responses, one-step strategies and two-step strategies, depending on whether the correction was applied in the slip step or in the following step. Responses that continue the slipping step produce smoother recoveries but only for higher friction coefficients. Responses that abandon the slipping step are capable of negotiating surfaces with a larger range of friction coefficients but accumulate larger errors. Knowledge of the environment is required to choose the best strategy. If friction coefficient estimates were known *a priori* or could be computed, they could be used to select the appropriate strategy to avoid slipping.

Our slipping simulations focused on traversal of a single patch in which one footfall slipped; however, some observations can be made regarding running on a slippery surface. For higher coefficients of friction, the strategies with the smallest errors, the foot force and hip torque reactions, are most likely to succeed. The repositioning strategies are limited because continual slipping would cause them to abandon every other step. However, all of the reflexive strategies except the hip torque strategy reduce the forward velocity during slip recovery, thus making the foot forces more vertical on subsequent steps. Preliminary results indicate that only a few slipping reactions may be required to achieve steady non-slipping running on a slippery surface.

If the foot is moving with respect to the ground at touchdown, the horizontal force on the ground is increased in the direction of motion, thereby increasing the danger of slipping. Strategies for running on slippery surfaces should try to reduce the relative motion of the foot between the ground prior to impact. This principle, which we call *ground-speed matching*, is useful in slip prevention. It also reduces the impact of ground contact and is used by animals and human runners.

For tripping, we evaluated several reflexes that repositioned the foot to find a viable foothold or to avoid the box completely. For trips that impacted the front-face of the box, lifting either the front or rear foot allowed successful recoveries. However, lifting the front foot produced the lowest errors at the start of the subsequent step. For trips in which the rear leg hit the box, pulling the leg back to let it pass over the box allowed the robot to continue running, but with some additional error in body attitude.

Slipping and tripping reflexes are fundamental to many rough terrain problems. Slopes, uneven surfaces, and small obstacles create oblique impact angles that can cause slips and trips. Reflexive responses will facilitate successful traversal of these terrains. Even with planning and sensing to avoid or anticipate known areas of rough terrain, a successful rough terrain robot will need slipping and tripping reflexes for error recovery combined with other primitives including reflexive strategies for adhesions, slopes, and loss of firm footing.

VIII. Acknowledgments

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NATIONAL SCIENCE FOUNDATION FINAL PROJECT REPORT

PART I - PROJECT IDENTIFICATION INFORMATION

1. Program Official/Org.
2. Program Name Robotics and Machine Intelligence
3. Award Dates (MM/YY) From: 930901 To: 970228
4. Organization and Address
5. Award Number IRI-9309187
6. Project Title RIA: Developing Reflexes for Robots: Recovery from Mechanical Errors

NSF Grant Conditions (Article 17, GC-1, and Article 8, FDP-II) require submission Project Report (NSF Form 98A) to the NSF Program Officer no later than 90 days after the expiration of the award. Final Project Reports for expired awards must be received before new awards can be made (NSF Grants Policy Manual Section 340).

Below, or on a separate page attached to this form, provide a summary of the completed projects and technical information. Be sure to include your name and award number on each separate page. See below for more instructions.

PART II - SUMMARY OF COMPLETED PROJECT (for public use)

The summary (about 200 words) must be self-contained and intelligible to a scientifically or technically literate reader. Without restating the project title, it should begin with a topic sentence stating the project's major thesis. The summary should include, if pertinent to the project being described, the following items:

- The primary objectives and scope of the project
- The techniques or approaches used only to the degree necessary for comprehension
- The findings and implications stated as concisely and informatively as possible

Many robot applications require legged robots to traverse rough or unmodeled terrain. This project explored strategies that would enable legged robots to respond to two common types of surface contact error: slipping and tripping. Because of the rapid response required and the difficulty of sensing uneven terrain, reflexes that allow the system to react without modeling or analyzing the error condition in detail are required. Reflex responses are unlike most robot control algorithms because of the time constraints of a rapidly evolving dynamic system and because of the need to respond to discontinuous events. This research demonstrated the effectiveness of preprogrammed high-level responses to errors during locomotion in a simulated, complex dynamic environment. A suite of responses allowed a simulated, three-dimensional, bipedal robot to recover from slipping on surfaces with varying friction and tripping over small obstacles of various heights.

PART III - TECHNICAL INFORMATION (for program management use)

List references to publications resulting from this award and briefly describe primary data, samples, physical collections, inventions, software, etc., created or gathered in the course of the research and, if appropriate, how they are being made available to the research community. Provide the NSF Invention Disclosure number for any invention.

Boone, G.N., Hodgins, J.K., 1997. Slipping and Tripping Reflexes for Bipedal Robots. Autonomous Robots, in press.

Boone, G.N., Hodgins, J.K., 1995. Reflexive Responses to Slipping in Bipedal Running Robots. IEEE/RSJ International Conference on Intelligent Robot and Systems

I certify to the best of my knowledge (1) the statements herein (excluding scientific hypotheses and scientific opinion) are true and complete, and (2) the text and graphics in this report as well as any accompanying publications or other documents, unless otherwise indicated, are the original work of the signatories or of individuals working under their supervision. I understand that willfully making a false statement or concealing a material fact in this report or any other communication submitted to NSF is a criminal offense (U.S. Code, Title 18, Section 1001).

	6/27/97
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PART IV - FINAL PROJECT REPORT -- SUMMARY DATA ON PROJECT PERSONNEL

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The data requested below are important for the development of a statistical profile on the personnel supported by Federal grants. The information on this part is solicited in response to public Law 99-383 and 42 USC 1885C. All information provided will be treated as confidential and will be safeguarded in accordance with the provisions of the Privacy Act of 1974. You should submit a single copy of this part with each final project report. However, submission of the requested information is not mandatory and is not a precondition of future award(s). Check the "Decline to Provide Information" box below if you do not wish to provide the information.

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	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.
A. Total, U.S. Citizens		1			2	1				
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U.S. Citizens or Permanent Residents:[2] American Indian or Alaskan Native....										
Asian...										
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Autonomous Robots, in press

Slipping and Tripping Reflexes for Bipedal Robots

Gary N. Boone and Jessica K. Hodgins

Abstract— **Many robot applications require legged robots to traverse rough or unmodeled terrain. This paper explores strategies that would enable legged robots to respond to two common types of surface contact error: slipping and tripping. Because of the rapid response required and the difficulty of sensing uneven terrain, we propose a set of reflexes that would permit the robot to react without modeling or analyzing the error condition in detail. These reflexive responses allow robust recovery from a variety of contact errors. We present simulation trials for single-slip tasks with varying coefficients of friction and single-trip tasks with varying obstacle heights.**

Keywords— **reactive control, reflexes, rough terrain, slipping, tripping, biped locomotion**

I. Introduction

ROUGH terrain occurs not only in natural environments but also in environments that have been constructed or modified for human use. Currently, most legged robots lack the control techniques that would allow them to behave robustly on such relatively simple rough terrain as stairs, curbs, grass, and slopes. Even smooth terrain becomes difficult to traverse if it includes small obstacles, loose particles, and slippery areas. Many control systems for bipedal robots have assumed steady-state running over smooth surfaces, but some have explored control techniques for rough terrain. Statically stable robots, which always maintain their balance over at least three legs, have used controllers with foot-placement algorithms to insure viable footholds. However, for dynamically stable robots, which run with a ballistic flight phase, constraints on timing and foot placement increase the difficulty of designing controllers that can anticipate rough terrain or react to errors. This paper demonstrates the effectiveness of preprogrammed high-level responses to errors during locomotion in a complex dynamic environment. A suite of responses allows a simulated, three-dimensional, bipedal robot to recover from slipping on low friction surfaces and tripping over small obstacles (Figure 1).

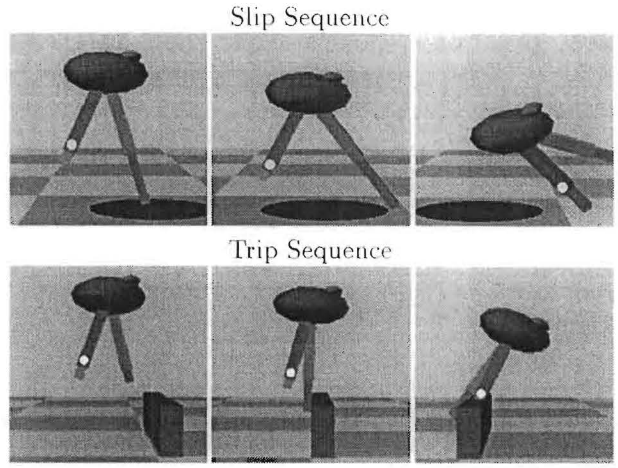

Fig. 1. **Examples of a Slip and Trip.** Without the addition of reflexes for recovering from slips and trips, the simulated robot does not respond successfully to slippery areas or contact with an obstacle.

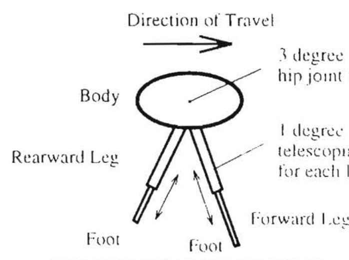

Fig. 2. **Biped Structure.** The simulated bipedal robot consists of a body and two telescoping legs. Each leg has three degrees of freedom at the hip and a fourth degree of freedom for the length of the leg.

Many ground contact errors would be avoided if the control system could guide the robot around slippery areas and obstacles. However, the approximate nature of sensor information obtained at a distance means that it is not always possible to sense the surface properties of terrain before making contact. For example, small holes, bumps, debris, and sticky or slippery areas are difficult to detect from a distance with current technology. If the robot cannot detect and avoid or prepare for surface features in advance, then robust locomotion on rough terrain requires that the robot respond to unexpected features after the contact error has occured and before the robot crashes. For dynamically stable robots, the time available for modeling the surface and planning an appropriate reaction is severely limited. In the case of the dynamically stable bipedal robot shown in Figure 2, the controller may have less than a few hundredths of a second in which to choose or plan an appropriate recovery.

We define *reflexes* as responses with limited sensing and no explicit modeling. That is, the robot can detect a slip or a trip, but makes no attempt to estimate the properties of the surface or obstacle or to calculate a corresponding recovery plan. Instead, the slipping and tripping sensors trigger fixed responses. These reflexes are defined at a high level, such as reconfigurations of the leg positions, and at a low level, such as modifications of servo gains. Just as animal motor programs can be considered both open-loop and closed-loop[1], several low-level feedback control laws operate during the primarily open-loop reflex responses. For example, a reflex may reconfigure the leg position, but sensing is used to determine transitions in the leg controller state machine during the recovery step.

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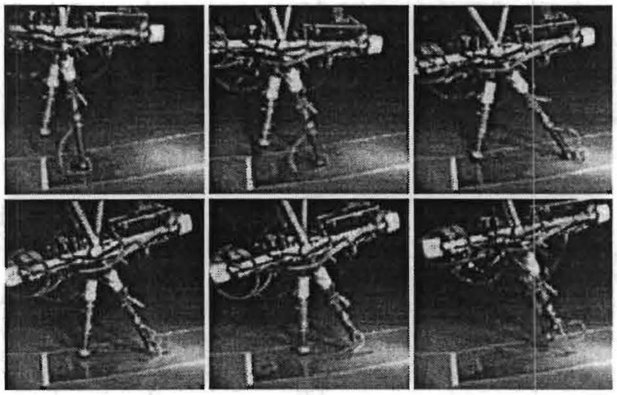

Fig. 3. **Physical Biped Slip.** Planar two-legged robot running across an oily spot on the floor. Footage from the MIT Leg Laboratory. [Frames: 0, 35, 70, 91, 105, 140]

During experimentation with a physical, planar biped, the robot sometimes slipped on hydraulic oil or tripped on cables in its path. Because the robot had no responses customized for these error conditions, it almost always immediately crashed. This paper reports a set of fixed reflexes that enable robust recoveries for a simulated three-dimensional robot in tasks involving a single slip or trip.

In the next section, we describe previous approaches to legged locomotion in rough terrain. In Section III, we consider biological reflexes. Section IV describes the simulated bipedal robot and its control system. The slipping problem, slipping reflexes, and simulation results are presented in Section V, followed by the tripping problem, tripping reflexes, and results in Section VI. The reflex approach and results are discussed in Section VII.

II. Locomotion on Rough Terrain

A suitable foothold is one that allows a legged system to maintain balance and continue walking or running. For statically stable locomotion, the difficulty is not in placing the robot's feet on footholds, but in deciding which locations on the terrain provide suitable footholds. Successful locomotion on rough terrain was demonstrated by the Adaptive Suspension Vehicle[2] and by the Ambler[3], [4], [5]. These large, statically stable machines traversed grassy slopes, muddy cornfields, and surfaces that included railroad ties and large rocks. Static stability allowed these robots to emphasize detection at a distance and avoidance of obstacles and uncertain footholds.

Klein and Kittivatcharapong[6] proposed algorithms for insuring that foot forces remain within the friction cone and identifying situations in which these constraints, or the desired body forces and torques, could not be achieved. Their work addressed prevention of slipping and did not consider sensor noise or responses to unmodeled surfaces.

For dynamically stable robots, the control of step length for locomotion on rough terrain interacts with the control of balance. Hodgins and Raibert[7] implemented three methods for controlling step length of a running bipedal robot. Each method adjusted one parameter of the running cycle: forward running speed, running height, or duration of ground contact. 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. However, unlike the tasks described below, the size and location of the objects were known to the controller in advance.

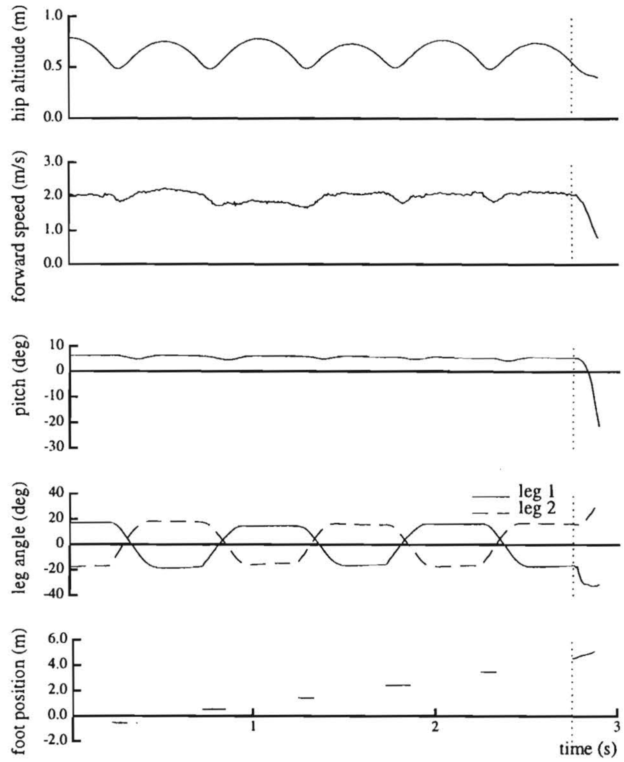

Fig. 4. **Slipping Data of the Physical Robot.** The physical planar robot slipped on oil during a laboratory experiment at the point indicated by the vertical dotted lines. The top three graphs show the height, forward speed, and orientation of the body. The bottom two graphs show the angles of each leg and the position of each foot on the ground. For each step but the last, the foot is stationary while it is on the ground.

Nagle[8] developed algorithms for running on terrain that was known to be slippery. By running slowly, the robot generated nearly vertical foot forces. His controller used *a priori* knowledge or estimation of friction coefficients to prevent slipping by confining control forces and torques to slip-free regions.

Kajita and Tani[9] used an ultrasonics sensor to construct a ground profile of terrain that consisted of horizontal surfaces at varying heights. Yamaguchi *et al* have built a bipedal robot that uses feet to sense ground inclinations and plan appropriately[10], although it was not able to react to slips or trips.

III. Reflexive Responses to Errors

Biological systems use many different reflexes in locomotion and manipulation. Reflexes help to restore balance when perturbations occur during walking or standing[11], [12], [13]. The role of reflexes in walking is complex: the same stimulus elicits a different response in the stance phase than in the swing phase[14], [15], [16]. Touching the foot of a cat or human during a swing phase, for example, will cause the leg to flex, raising the foot. If an obstacle caused the stimulus, this response might lift the foot over the obstacle and allow walking to continue. During the stance phase, a stimulus delivered to the foot causes the leg to push down harder, resulting in a shorter stance phase. Although these actions are opposite, both facilitate the continuation of locomotion.

Robotics has adopted the term "reflex" from the biological literature, but in both biology and robotics the precise definition of the term varies from study to study. Most researchers in robotics use the term to mean a quick response initiated by sensory input. Some require reflexes to be open-loop and to proceed independently of subsequent sensory input[17], [18]; others apply the term more loosely to describe actions that are performed with feedback until a terminating sensory event occurs[19]. In some cases, reflexes refer to general purpose actions[20], [21] and in others only to actions taken to correct errors or to compensate for disturbances[19] or transitions[22].

Brooks's subsumption architecture[21] combined several simple reflex-like actions to produce complex behaviors such as six-legged walking. A global gait generator specified the order of leg use while inhibitory connections between the legs prevented conflicting reflexes from acting simultaneously. Other hexapod robot researchers have designed subsumption controllers for rough terrain[23] and have integrated reactive leg control with gait planning for rough terrain[24].

Hirose[20] built and controlled a statically stable quadruped that used a reflexive probing action to climb over objects and to walk up and down steps without visual input or a map of the terrain.

Wong and Orin[19] implemented two reflex responses for a prototype leg of the Adaptive Suspension Vehicle. Using velocity and hydraulic pressure information from sensors at the joints, they were able to detect foot contact and slippage. A foot contact reflex reduced the peak forces at touchdown. A foot slippage reflex was used to detect and halt slipping.

Reflex responses have also been used in manipulation. Tomovic and Boni[17] used a reflex response to implement grasping for the Belgrade prosthetic hand. Bekey and Tomovic[18] continued the exploration of prosthetic control systems with a rule-based technique that relied on sensory data and fixed response patterns.

IV. Dynamic Bipedal Robots

The simulated robot used in our research is based on a planar bipedal robot constructed by Raibert and colleagues[25], [26]. The simulated robot is three-dimensional and has three controlled degrees of freedom at each hip and one for the length of each leg (Figure 2). In the physical robot, the leg contains a hydraulic actuator in series with an air spring. The simulation models the spring and actuator as a linear spring with a controllable rest length. In experiments with the physical robots, hydraulic fluid occasionally created slippery spots that caused the robot to fall (Figures 3 and 4). A simulation of a similar fall is plotted in Figures 5 and 6. The physical robot was also able to climb stairs and jump over boxes[26]; however, the positions of the obstacles were known in advance. The current research extends the controller to handle unexpected slips and unanticipated collisions with a box.

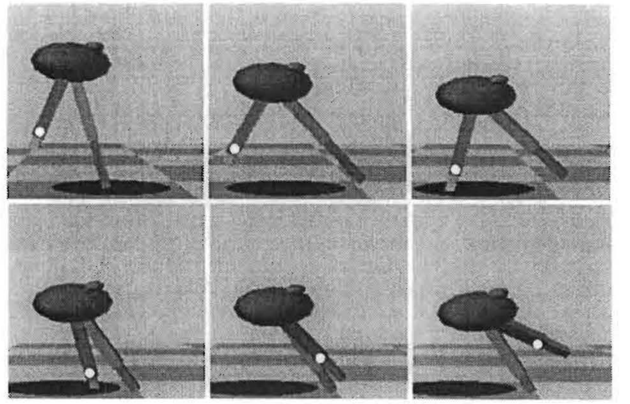

Fig. 5. **Simulated Biped Slip.** The dark circle represents an area of the floor with a reduced coefficient of friction. Without slipping reflexes, the simulated robot is unable to complete a step on a slippery surface. The first leg slips, almost immediately becoming airborne as it accelerates forward. As the body falls, the second leg hits the surface and also slips. The second leg continues to accelerate forward. [Friction coefficient: 0.04. Times (s): 0.0, 0.06, 0.09, 0.11, 0.12, 0.13]

The simulation includes the equations of motion, a control system for bipedal running, a graphical model of the robot, and a user interface for interacting with the simulation. The equations of motion for the robot were generated using a commercially available package[27]. The parameters of the simulated robot are based on the physical robot. Neither the physical nor simulated robot had foot structures beyond contact switches. Also, natural legs are rotationally jointed rather than telescoping. Thus, the reflex responses described below apply to interactions between a simple leg geometry and the environment. However, the responses themselves do not depend on the leg geometry, assuming only that the foot can be pressed or repositioned.

The controller achieves dynamically stable, steady-state running by decomposing the control problem into three largely decoupled subtasks: hopping height, forward velocity, and body attitude. Hopping height is maintained by adding enough energy to the spring in the leg during stance to account for the system's dissipative losses. Forward velocity is maintained by choosing a leg angle at touchdown that provides symmetric deceleration and acceleration as the leg compresses and extends. The attitude of the body (pitch, roll, and yaw) is maintained with proportional-derivative servos that apply torques between the body and the leg while the foot is on the ground.

The robot control system is implemented as a state machine that sequences through the flight and stance phases for each leg, applying the control laws that are appropriate for each state. As shown in Figure 7, *flight* is fol-

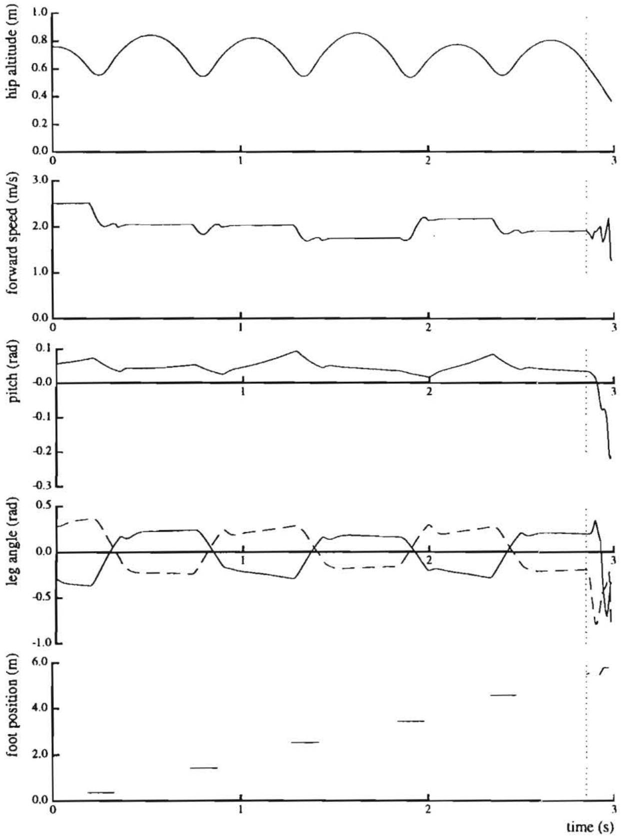

Fig. 6. **Slipping Data of the Simulated Robot.** After taking five steps on a surface with a friction coefficient of 1.0, the simulated robot steps on a region with a coefficient of 0.20 and slips. Because no slipping recovery strategies are active, the robot falls. The top three graphs show the height, forward speed, and orientation of the body. The bottom two graphs show the leg angles of both legs and the position of each foot on the ground. When the foot slips (vertical dotted line), it leaves the ground and the other foot soon impacts.

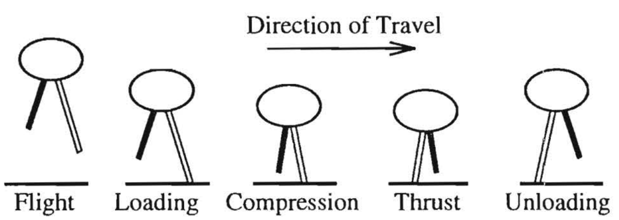

Fig. 7. **Control States.** Running is achieved by dividing each step into several states and applying the appropriate control laws during each part of the running step.

lowed by a stance phase of four states. During *loading*, the foot makes contact with the ground and begins to bear the weight of the robot. During *compression*, the leg spring is compressed by the downward velocity of the robot. After the spring has stopped the vertical deceleration of the body, the body begins to rebound during *thrust*. As the leg reaches maximum extension during *unloading*, it ceases to bear weight. After liftoff, the roles of the legs are reversed and the second leg is positioned forward in anticipation of touchdown. For further details on the control system, see [26] and [25].

The control system's state machine depends on measurements of leg length to determine state transitions during steps. Slips may interfere with control by altering leg lengths unexpectedly. The transition from loading to compression, for example, occurs when the leg has shortened by a small amount. After a slip, the leg may lengthen. Not only must slipping reactions prevent these errors, but they must minimize interference with normal control, such as the adjustment of body attitude.

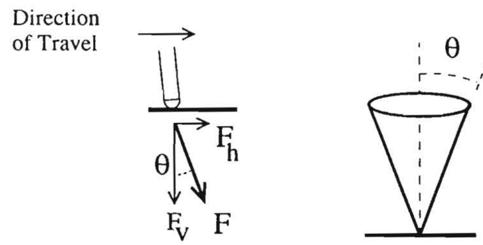

Fig. 8. **Foot Forces and the Friction Cone.** During a step, the foot produces forces on the ground, F, with horizontal and vertical components, F_h and F_v. Slipping occurs when the angle of the impact force is outside the friction cone.

V. Slipping

The impact of the foot on the ground, the weight of the robot, and the forces and torques generated by the hip and leg servos create a force on the ground during a step (Figure 8). Slipping occurs when the horizontal component of the force of the foot on the ground, F_h, exceeds the maximum force of static friction generated by the ground. A simple model of this interaction is that the maximum force of static friction is directly proportional to the normal force of the ground on the foot, F_v. Under this model, slipping will occur when the horizontal component of F exceeds the vertical component times the coefficient of static friction:

$$F_h > \mu_s F_v,$$

where μ_s is the coefficient of static friction. When slipping occurs, the horizontal force returned by the ground is given by

$$F_h = \pm \mu_d F_v,$$

where μ_d is the coefficient of dynamic friction and the sign of F_h should remain unchanged. These relationships define a *friction cone*, illustrated in Figure 8. When the force of the foot on the ground lies within the friction cone, the foot does not slip. The angle of the cone is given by

$$\theta_{max} = \tan^{-1} \mu_s.$$

Note that this cone is defined for foot forces, not leg angles. The motion of the leg prior to impact affects the direction of the foot's force on the ground, as do the control torques applied to the hip joint and the leg spring. Foot forces are most likely to exceed the friction cone at the beginning or end of a step, when the angle of the force vector is greatest. Slips at the beginning of a step are more likely than slips at liftoff because the foot is moving with respect to the ground at touchdown. In contrast, the foot is stationary at

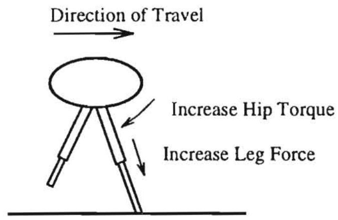

Fig. 9. **Same-Step Reactions.** When a slip has been detected, a torque can be applied at the hip to reduce the horizontal force on the ground or the leg can be extended to increase the vertical force.

liftoff. Slips during liftoff are often less critical because the step is nearly complete; the controller has already executed corrections during the step.

Our simulations assumed minimal sensory information: the properties of the surface and the extent of the slipping area were not available to the control system. The controller could not adjust the leg configuration prior to touchdown or try to position the foot outside the slippery area to find a secure foothold. Neither the forces on the feet nor the coefficients of friction were available to the control system. However, the control system could detect slips. In the simulation, slips were detected when a foot moved while in contact with the ground. The control system of a physical robot can detect slips indirectly by measuring joint angles and velocities or structural forces. For example, assuming no other contacts, sudden changes in hip angle while the foot is on the ground indicate a slip. Direct methods include encoder wheels and micro-slip detectors.

When the control system has detected a slip, it can attempt to continue the step or abandon that step and pull the leg off the ground. In the first case, hip torques or leg forces can be applied to increase the vertical component of the foot force while decreasing the horizontal component, thus returning the force vector to within the friction cone. If the step is abandoned, one of the legs can be positioned during the next flight phase so that the leg angle at the next touchdown will be near vertical or both legs can be moved to a triangular configuration. In the simulations described here, we defined a response to be successful if the robot was able to continue running after slipping and taking a recovery step in the slippery region, then taking subsequent steps on a non-slippery surface. Changes in velocity or hopping height were not considered failures provided that the control system was able to maintain balance and return to steady-state running.

A. Same-Step Response Strategies

Reacting to a slip requires careful management of the horizontal and vertical components of the forces generated by the impact of the foot on the ground. Initial responses to a slip can attempt to alter the force vector immediately by generating a torque at the hip or a force axial to the leg (Figure 9).

The first reaction responds to a slip by increasing the hip torque by a fixed amount. In most cases, this action increases the vertical component of the foot's force

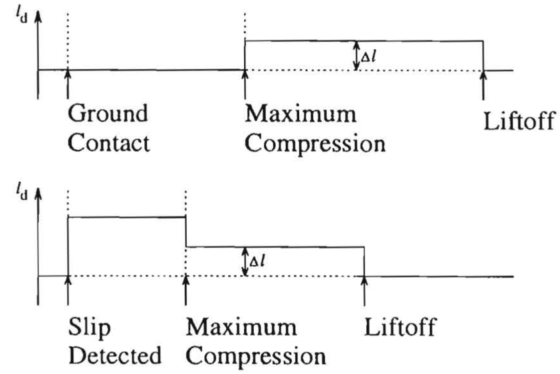

Fig. 10. **Forcing the Foot into the Ground.** In a normal step (top), energy is added into the leg spring at the moment of maximum compression. In the forced step (bottom), the loading on the leg is increased just after touchdown, forcing the foot into the ground and shortening the step duration. l_d is the desired leg length. Δl is the change in desired leg length that returns the robot to the desired hopping height.

on the ground. After the foot stops slipping, the hip controller reverts to its normal task of correcting pitch errors. This strategy may have undesirable consequences because a torque applied at the hip also increases the forward velocity of the body thus increasing the likelihood of a slip on a subsequent step. Applying a torque at the hip also interferes with the correction of body attitude during stance and tends to increase the pitch of the body.

The second reaction responds to a slip by compressing the leg spring a fixed amount to increase the vertical force at the foot and regain a foothold. In a normal running step, the leg spring stores energy during the stance phase and causes the body mass to have approximately equal and opposite vertical velocities at liftoff and touchdown. To maintain the duration of flight, the control system lengthens the leg to add energy equivalent to that lost due to internal mechanical losses and to the impact of the unsprung mass of the lower leg with the ground. In a normal step, thrust occurs at the moment of maximum compression of the spring (Figure 10). In responding to a slip, the control system may alter this sequence by extending the leg as soon as the slip is detected. If the leg is close to vertical, this extension increases the vertical component of the foot's force on the ground and may stop the slip. The extension also adds energy into the leg spring. The extra energy is removed later in the step by lengthening the leg spring when the leg is vertical, leaving the hopping height unchanged (Figure 10).

One effect of this reaction is to slow the robot, a desirable effect when the surface is slippery. However, the foot forcing reflex may lead to a crash if the leg geometry and velocity is such that extending the leg increases the horizontal forces on the foot more than the vertical forces. Thus, the foot forcing reflex may not be sufficient in itself to recover from slips.

The foot forcing reaction shortens the period of time during which the spring is passively compressed, leading to a shorter stance phase and a style of running that utilizes

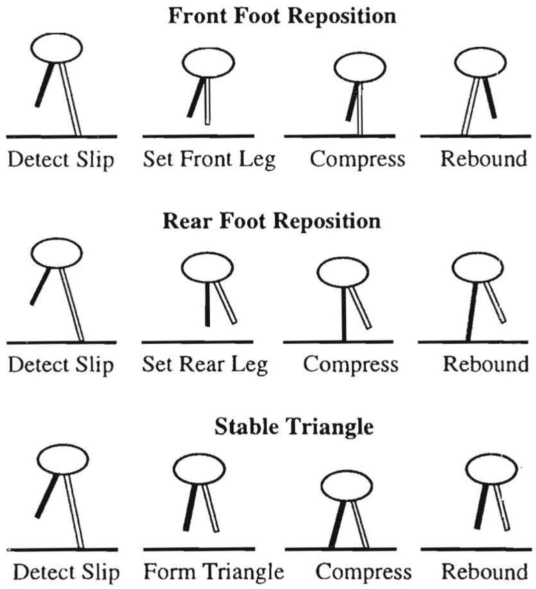

Fig. 11. **Repositioning Strategies.** After a slip has been detected, the initial step is abandoned and one or both legs are repositioned for the next step. The leg angle at touchdown on the next step will be closer to vertical, keeping the impact force vector within the friction cone.

quick hops rather than long strides. We have observed that this quick-stepping behavior is a useful method for running briefly on slippery surfaces because the leg angle at touchdown is near vertical. However, the shorter stance phase also reduces the available time for correcting the body attitude and makes steady-state running difficult to achieve.

B. Repositioning Strategies

The step on which the initial slip occured may be abandoned by immediately lifting the foot; the resulting flight phase provides a brief opportunity to prepare for another landing on the slippery surface. By reconfiguring the legs during the flight phase following the initial slip, the control system can attempt to keep the foot forces within the friction cone. Because the coefficient of friction is not known, the size of the friction cone is unknown. Therefore, the best place for the foot at the next touchdown is directly under the body, making the leg vertical at touchdown. Figure 11 diagrams the strategies that reposition the legs. Figures 12, 13, and 14, contain sequences showing the repositioning strategies involved in recovering from a slip.

After a slip has been detected, both legs may be used in the recovery by configuring them in a narrow fixed triangle vertically centered under the body. The control system attempts to hold this triangle throughout the subsequent step and does not apply the normal pitch, roll, and yaw adjustments. Instead, the robot bounces, letting the geometric configuration provide stability rather than using active control. The leg angles in normal running are nearly symmetric during the flight phase of steady-state running; the control system only has to equalize the leg lengths to create a symmetric triangle. Because the extent of the friction cone is unknown, the triangle is narrowed so the legs are close to vertical. When both feet contact the ground, foot forcing is applied to each to reduce the time of stance. After both feet have lifted off the ground, the control returns to a normal flight state.

C. Slipping Results

The slipping strategies were tested in simulation by varying the initial velocity of the robot and the coefficient of friction to produce multiple runs. For each trial, a circular slippery area was simulated at the location of the first footfall. During successful runs, the robot stepped once in the slippery area and then five additional times on a non-slippery surface. Because the body of the robot is closer to the ground at higher speeds, making the problem harder, we chose velocities near the controllers maximum speed for stable running. The initial velocity was 2.5 ± 0.25 m/s. The size of the slippery area for each reaction strategy was large enough to prevent a foot from sliding to the edge, a situation that allowed an easy recovery. The slippery area was small enough that subsequent footfalls were located outside of it. Twenty friction coefficients between 0.025 and 0.5 were used. Both static and dynamic coefficients were set to the same value for each trial of 20 simulations with different initial velocities. The robot was judged able to recover from a slip at a given coefficient of friction if at least half of the trials were completed successfully.

For the successful trials, we computed a measure of the error at touchdown of the step after the recovery step that followed the slip. The error measure was the summed absolute values of differences between the actual and desired angles for the body yaw, α, pitch, β, and roll, γ:

$$\text{Error} = |\alpha - \alpha_d| + |\beta - \beta_d| + |\gamma - \gamma_d| .$$

The error calculation was designed to measure how well the slip recovery strategy had positioned the robot after the slip step, the recovery step, and the subsequent ballistic flight. The errors for the successful trials were averaged to compute the data shown in Figure 15. This graph illustrates the tradeoff between the two types of strategies.

With no active reflexes, the controller is able to negotiate friction coefficients as low as 0.28. Upon contact, the foot slides; as it is loaded, the vertical and horizontal forces increase, pushing the foot back under the body. Eventually the forces on the foot reenter the friction cone, slipping ceases, and a normal step ensues. The foot forcing strategy causes the foot to slide further out from under the body, leading to fewer recoveries at lower coefficients of friction than the steady-state control system. We observed this effect for several running speeds and heights. However, it may be a consequence of the geometry of the robot design; foot forcing may be useful for slow moving robots or those with other gait patterns. The hip torque reflex succeeds at pulling the leg back and enables recoveries as low as 0.22. Note that hip torque does indeed increase the body pitch, producing increased errors shown in the graph.

The repositioning strategies delay error correction while the legs are reconfigured. As a result, the repositioning

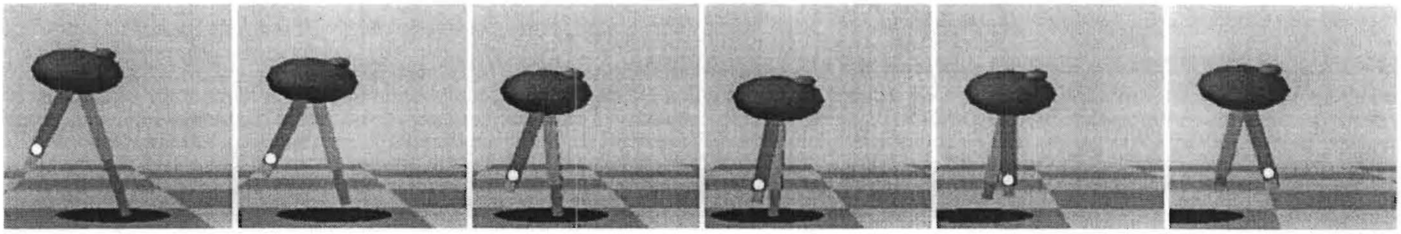

Fig. 12. **Front Leg Repositioning.** The front leg is lifted and repositioned for a more vertical impact. [Friction coefficient: 0.20. Times (s): 0.0, 0.02, 0.05, 0.07, 0.12, 0.15]

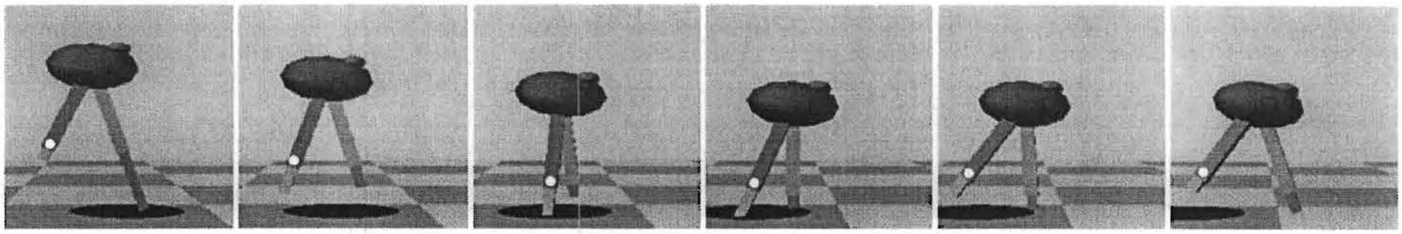

Fig. 13. **Rear Leg Repositioning.** The rear leg is brought under the slipping robot to arrest the fall. The newly planted leg slips upon takeoff, but the step is successful because the body attitude is not disturbed significantly. The robot is able to continue running. [Friction coefficient: 0.20. Time (s): 0.0, 0.04, 0.07, 0.12, 0.13, 0.16]

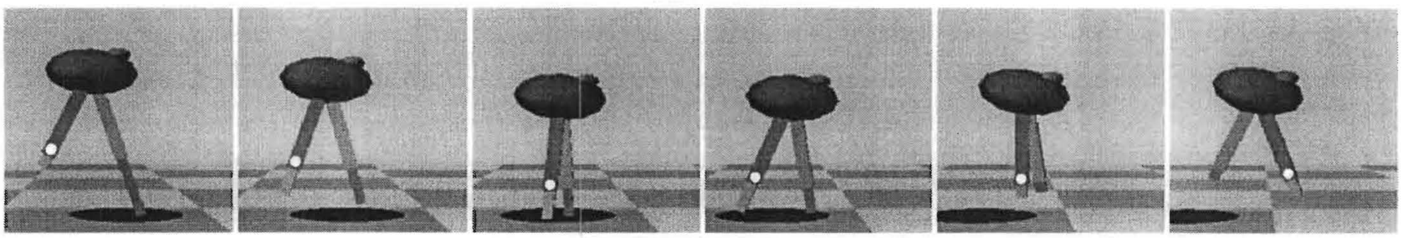

Fig. 14. **Stable Triangle Recovery.** After detecting a slip, the robot forms a stable triangle. Although the legs slip just prior to liftoff, the control system is able to recover because the slip is symmetric and occurs at the end of the step. [Friction coefficient: 0.02. Times (s): 0.0, 0.03, 0.07, 0.10, 0.14, 0.19]

strategies produce larger errors upon return to normal running than the foot forcing and hip torque reflexes. However, the repositioning strategies are able to recover from slips on surfaces with smaller coefficients of friction. By lifting the leg and repositioning it within the friction cone, the front and rear repositioning reflexes are able to recover from surfaces with coefficients as low as 0.07 and 0.15, respectively. The front repositioning strategy is more successful than the rear repositioning strategy because it more effectively reduces the relative speed of the foot over the ground before impact. Because the robot is moving forward while the foot is airborne, bringing the rear leg forward increases the relative speed between the foot and the ground. The front repositioning strategy brings the front leg back, reducing the relative speed. On impact, the foot with the lower relative speed is subjected to smaller horizontal forces and is less likely to slip.

The robot experiences increased slipping as the coefficient of friction decreases, but it often recovers because the slips occur at the end of the recovery step. Figure 13 shows a normal ground contact and rebound followed by a slip upon takeoff. Because the hopping height, forward speed, and body attitude control algorithms have already been applied, the slip has little effect on the configuration

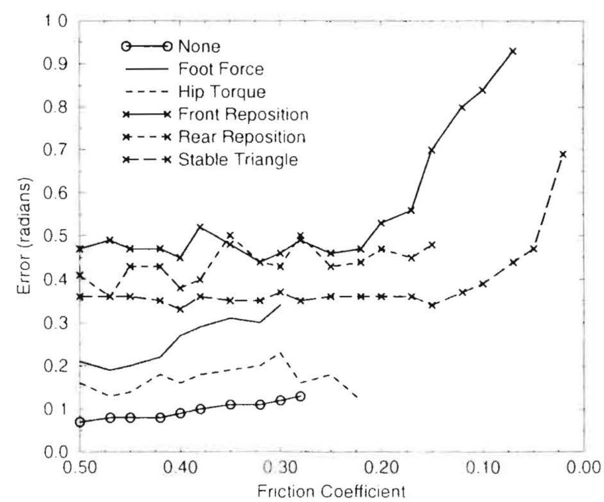

Fig. 15. **Touchdown Errors.** If the robot recovers from a slip, it starts the next step with some error. This graph illustrates the tradeoff between smooth running and slip recovery. Lower curves indicate smaller errors in body and leg angle. Longer curves indicate that a greater range of friction coefficients can be tolerated.

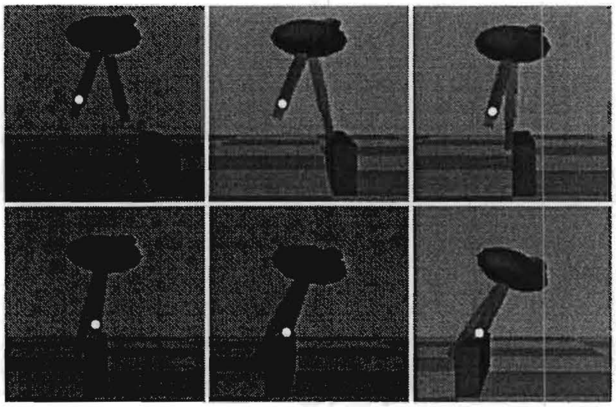

Fig. 16. **Simulated Trip.** The front foot contacts the vertical face of a box and slides down the surface. With no response, the robot is unable to continue running and crashes. [Times (s): 0.0, 0.05, 0.09, 0.13, 0.17, 0.20]

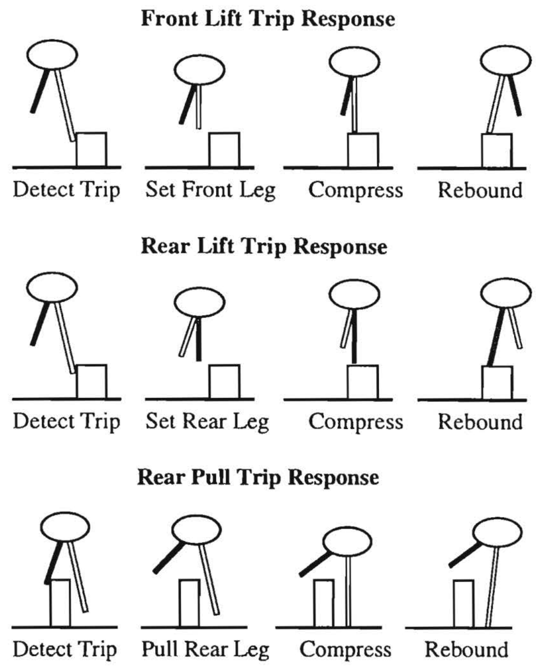

Fig. 17. **Trip Recovery Strategies.** After a trip has been detected, one of the legs is repositioned in an attempt to contact the top surface of the obstacle or avoid it entirely.

of the robot. Figure 14 shows slipping upon takeoff for the stable triangle strategy, which applies no attitude correction during the recovery step. However, as Figure 14 shows, both legs slip symmetrically, cancelling the effect of their torque on the body. Thus, the stable triangle reflex is capable of recovering from surfaces with coefficients as low as 0.025.

VI. Tripping

For steady-state running, the control system detects expected events, such as foot contact or initial leg spring compression, and uses these signals to transition between control states. During each state, it applies the appropriate collection of control laws. Tripping occurs when the robot feet or legs encounter unexpected obstacles, causing the controller to execute inappropriate servo commands (Figure 16).

To explore reflexive responses to tripping, we considered the task of returning the robot to steady-state running after a collision with a box. The existing controller allowed the robot to continue running for some unexpected contacts. For example, foot contacts on the top surfaces of boxes, though premature in the flight phase, allowed a normal step to occur. Oblique contacts, such as brushing the side of the box, also did not usually prevent running from continuing. Other contacts, such as a foot or leg contacting the vertical face of a box, resulted in crashes.

A. Tripping Responses

As in the case of slipping, the sensing requirements were minimal. The controller detected only that a contact with a foot or leg had occurred. It did not detect where on the leg the contact had occurred. These conditions could be determined on a physical robot with contact sensors on the legs or via the existing joint angle sensors.

When a leg or foot hits the front surface of a box, a foot must be repositioned to find a foothold on or beyond the box. If the forward foot hits the box, either the forward or the rear foot can be retracted and repositioned to contact the top surface of the box, where good footholds are available. We call these strategies the "front lift" and "rear lift" reflexes, depending on which leg is lifted to the top surface of the box. If the rear leg hits a box, the leg can be pulled back, allowing it to pass over the box without contact. We refer to this strategy as "rear pull." These reflexes are diagrammed in Figure 17 and shown in Figures 18, 19 and 20.

B. Tripping Results

To test the tripping reactions, boxes of varying heights were placed in the path of a robot running in steady state. For the front lift and rear lift reflexes, the vertical face of each box was divided into 20 impact heights and the robot was released with the front foot 2 cm from the box at each height. For the rear pull reflex, the robot was placed straddling boxes of varying heights with the forward foot making an initial ground contact in a normal running step. As the box height increased, the rear leg eventually contacted the box as it swung forward. In all simulations, the initial forward speed of the robot was varied by a small random factor.

With no reflex responses, the robot was unable to continue running following a trip. The front lift and rear lift response curves show that as the box heights increase, the tripping reflexes are less likely to produce a recovery (Figures 21 and 22). The number of crashes increases as the box height increases. This increase in crashes is due to the increasing distances to the box top as the height increases. If the foot hits the box near the top, there may be sufficient time to lift it to the top of the box. However, as the box height increases, fewer potential contact points are near the top edge of the box.

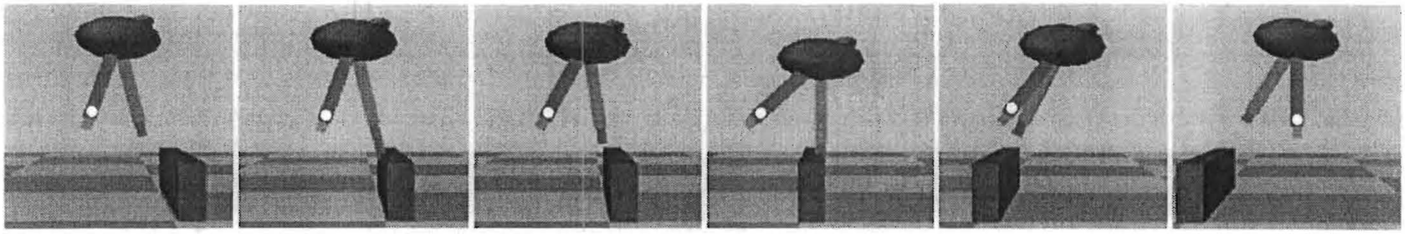

Fig. 18. **Front Lift Trip Response.** The front leg is lifted and repositioned to achieve a better foothold. [Times (s): 0.0, 0.04, 0.06, 0.13, 0.23, 0.27]

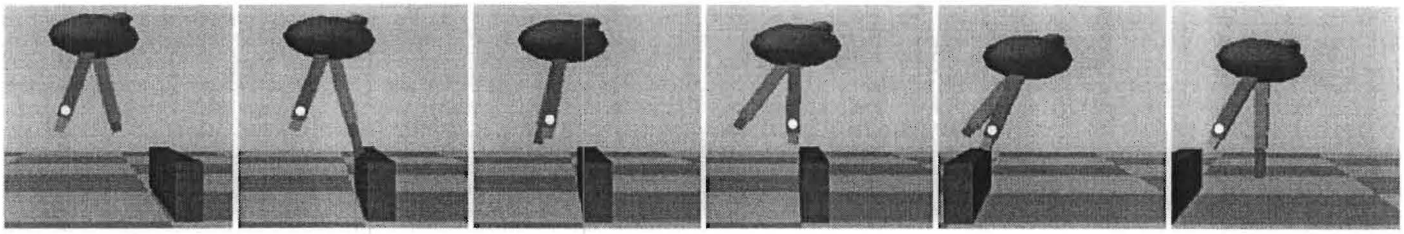

Fig. 19. **Rear Lift Trip Response.** The rear leg is lifted and repositioned to achieve a better foothold. [Time (s): 0.0, 0.07, 0.09, 0.11, 0.23, 0.28]

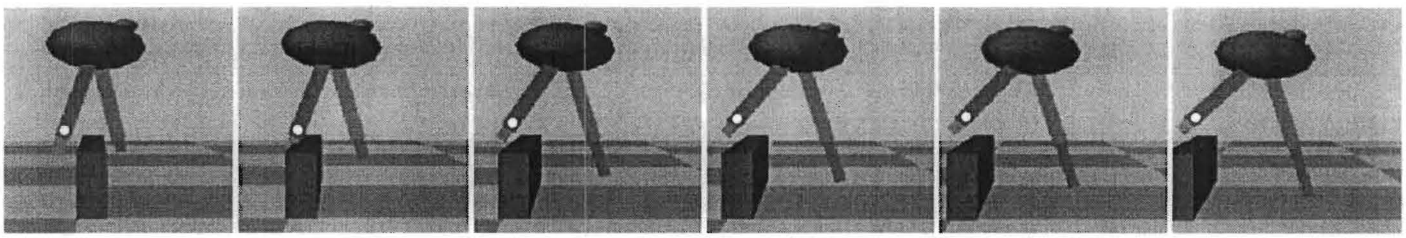

Fig. 20. **Rear Pull Trip Response.** When a leg hits an obstacle while swinging forward, it is pulled back to allow it to clear the obstacle. [Times (s): 0.0, 0.03, 0.06, 0.07, 0.08, 0.10]

To measure the disturbance to normal running, we computed the same error measure as was used in the slipping trials. The error measure was the sum of the absolute values of the errors between actual and desired yaw, α, pitch, β, and roll, γ:

$$\text{Error} = |\alpha - \alpha_d| + |\beta - \beta_d| + |\gamma - \gamma_d| .$$

The bottom graphs in Figures 21 and 22 show that if the robot is able to recover, it does so with approximately the same error independent of box height.

The front lift reflex causes less touchdown error than does the rear lift reflex. To recover with the front foot, the foot must lift over the box edge, whereas a recovery with the rear foot must move the rear foot from its position behind the robot to the box. The rear lift reflex accumulates more errors during the additional flight time.

With no reflex responses, the robot is unable to recover when the rear leg hits a box of any height. However, Figure 23 shows that pulling the leg back after the initial contact allows the robot to pass the leg over boxes as high as 23 cm without crashes. For boxes between 23 cm and 25 cm, the leg, though pulled back, hits the box again, but may still be able to recover. Above 25 cm, the boxes are too high for the retracted leg to pass over, increasing the number of crashes.

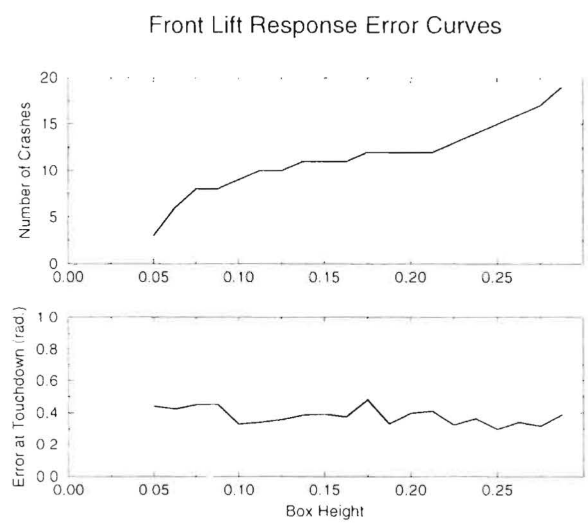

Fig. 21. **Front Lift Results.** The top graph shows the number of crashes as the obstacle height increases. The bottom graph shows the average error in body attitude at the start of the next step after recovering from a trip. As the box height increases, trips more often lead to crashes. Note however, that the errors remain relatively constant for those trials where the robot is able to recover and continue running. There were 20 runs per box height. Box heights below 5 cm did not cause trips; box heights above 28.75 cm did not allow recovery.

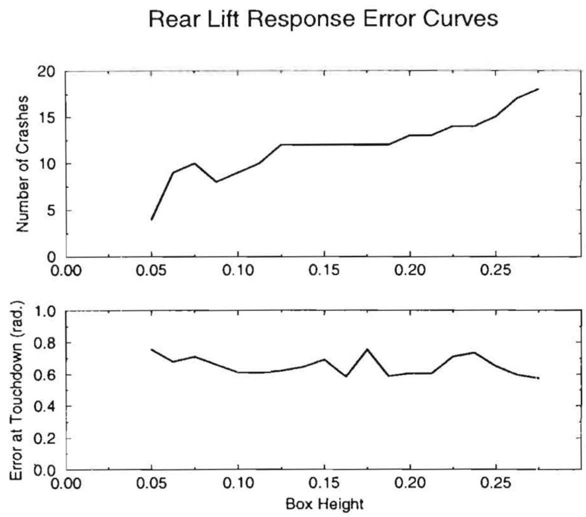

Fig. 22. **Rear Lift Results.** Taller boxes are more likely to cause a crash. However, if the robot does recover, it does so with a relatively constant error. The rear lift reflex recovers about as often as the front lift reflex (Figure 21), but with higher resulting errors. There were 20 runs per box height.

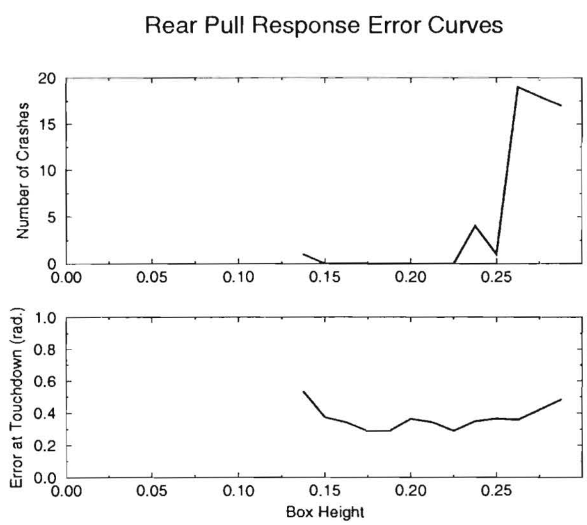

Fig. 23. **Rear Pull Results.** Pulling the tripping foot back so it passes over the box allows the robot to continue running, but with some additional attitude error. For box heights below 13.75 cm, the rear foot passes over the box without tripping due to the retraction of the leg during running. There were 20 runs per box height with variation in the initial velocity of the robot.

The tripping responses are not as robust as the slipping responses. In the slipping case, the response may apply body attitude control, as in the non-repositioning strategies, or will reposition the legs to a more vertical configuration, and will reduce the desired speed. These actions decrease the likelihood of another slip on the next ground contact. The trip responses, however, cannot reduce the likelihood of a subsequent trip because in the reflexive paradigm there is no planning to determine the desired interaction with the environment. If the first tripping response fails, the controller is unlikely to succeed by responding again in the same way.

VII. Discussion and Conclusions

We have considered the problem of creating reflexes for slipping and tripping given only the information that a slip or a trip has occurred. We evaluated two kinds of responses to slipping, one-step strategies and two-step strategies, depending on whether the correction was applied in the slip step or in the following step. Responses that continue the slipping step produce smoother recoveries but only for higher friction coefficients. Responses that abandon the slipping step are capable of negotiating surfaces with a larger range of friction coefficients but accumulate larger errors.

Our slipping simulations focused on traversing a patch in which one footfall slipped; however, some observations can be made regarding running on a slippery surface. For higher coefficients of friction, the strategy with the smallest errors, the hip torque reaction, is most likely to succeed. The repositioning strategies are limited because continual slipping would cause them to abandon every other step. However, all of the reflexive strategies except the hip torque strategy reduce the forward velocity during slip recovery, thus making the foot forces more vertical on subsequent steps. Preliminary results indicate that only a few slipping reactions may be required to achieve steady running on a slippery surface without slipping.

If the foot is moving with respect to the ground at touchdown, the horizontal force on the ground is increased in the direction of motion, thereby increasing the danger of slipping. Strategies for running on slippery surfaces should try to reduce the relative motion of the foot between the ground prior to impact. This principle, commonly called *ground-speed matching*, is useful in slip prevention. It also reduces the impact of ground contact and is used by animals and human runners.

We evaluated several reflexes that repositioned the foot after a trip to find a viable foothold or to avoid the box. For trips in which the forward foot struck the vertical face of the box, lifting either the front or rear foot allowed recoveries. However, lifting the front foot produced the smallest errors at the start of the subsequent step. For trips in which the rear leg hit the box, pulling the leg back to let it pass over the box allowed the robot to continue running, but with some additional error in body attitude.

The slipping and tripping reflexes have been validated for single slip or trip tasks. The next task is to integrate the reflexes to enable running through general rough terrain with arbitrary obstacles and slippery areas. Additional controllers may be used to select among the applicable reflexes based on sensing or modeling of the environment. Finally, within the time constraints of the rapidly evolving dynamic system, limited replanning may be used to aid recovery.

These slipping and tripping reflexes are robust despite their minimal sensing requirements. Without determining friction or obstacle properties, without modeling the surface, and without online planning, the reflexes enable the robot to continue running under many circumstances.

Even if more sensing and computational resources are available for foot placement, surface modeling, and replanning, reflexes such as these will remain necessary due to sensing and modeling errors.

Slipping and tripping reflexes are fundamental to many rough terrain problems. Slopes, uneven surfaces, and small obstacles create oblique impact angles that can cause slips and trips. Reflexive responses will facilitate the successful traversal of these terrains in combination with other reflexive strategies for foothold errors such as adhesions, bounces, and loss of firm footing.

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