Robotic walking in natural terrain

Gait planning and behavior-based control for statically-stable walking robots

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By David Wettergreen

The Robotics Institute
Carnegie Mellon University
5000 Forbes Avenue
Pittsburgh, PA 15213

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Abstract

A substantial portion of the Earth is inaccessible to any sort of wheeled mechanism—natural obstacles like large rocks, loose soil, deep ravines, and steep slopes conspire to render rolling locomotion ineffective. Hills, mountains, shores, seabeds, as well as the moon and other planets present similar terrain challenges.

In many of these natural terrains, legs are well-suited. They can avoid small obstacles by making discrete contacts and passing up undesirable footholds. Legged mechanisms can climb over obstacles and step across ditches, surmounting terrain discontinuities of body-scale while staying level and stable.

To achieve their potential, legged robots must coordinate their leg motions to climb over, step across and walk in natural terrain. These coordinated motions, which support and propel the robot, are called a gait. This thesis develops a new method of gait planning and control that enables statically-stable walking robots to produce a gait that is robust and productive in natural terrain.

Independent task-achieving processes, called gait behaviors, establish a nominal gait, adapt it to the terrain, and react to disturbances like bumps and slips. Gait controlled in this way enabled the robot Dante II to walk autonomously in natural terrain, including the volcanic crater of Mount Spurr. This method extends to other walking robots as demonstrated by a generalized hexapod that performs the variety of gaits seen in six-legged insects, as well as aperiodic free gaits. The ability to change gait patterns on-the-fly with continuous, stable motion is a new development that enables robots to behave more like animals in adapting their gait to terrain.

Finally, this thesis describes why walking robots need predictive plans as well as reflexive behaviors to walk effectively in the real world. It presents a method of guiding the behavior of a walking robot by planning distinct attributes of the desired gait. This partitioning of gait planning avoids the complexity of high degree-of-freedom motion planning. The ability to plan and foresee changes in gait improves performance while maintaining robust safety and stability.

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Chapter 1

Introduction

Mountain goats bound up steep cliffs, camels pace across shifting sands, gazelles pronk and leap huge obstacles. Elephants amble through dense jungles while carrying enormous loads, spiders crawl up walls, and cockroaches, virtually indestructible, explore the entire planet. What if robots could do these things too?

They may be able to someday, but they will be walking on legs instead of rolling with wheels. A substantial portion of the Earth is inaccessible to any sort of wheeled mechanism—natural obstacles like large rocks, loose soil, deep ravines, and steep slopes conspire to render rolling locomotion ineffective. More than half of the Earth's land area precludes wheeled and tracked vehicles. The sea floor, moon, and other planets are similarly challenging.

In many of these natural terrains, legs are well-suited. They can avoid small obstacles by making discrete contacts and by passing up undesirable footholds. Legged mechanisms can climb over large obstacles and step across ditches, surmounting terrain discontinuities of body-scale. They isolate their posture from the terrain, which minimizes required power, maximizes stability, and makes it possible to ascend and descend steep slopes. Animals do these things every day, but to follow in their tracks, robots will need legs.

There are many problems that need to be solved before walking robots parallel the capabilities of animals. One of the most fundamental is how to establish the coordinated leg motions that make the robot walk. These coordinated motions, which support and propel the walking robot or animal, are called a gait.

This is the problem that I address in this thesis: enabling a real walking robot to produce a gait that is robust and productive in natural terrain. I develop the claim that walking robots need both predictive plans and reflexive actions to walk effectively in the real world. I support this claim with demonstrations of walking by several robots. Along the way I discuss why walking robots need autonomy; what the benefits and shortcomings of planning are; how much, but not all of what walking entails can be produced by simple behaviors; as well as how animals apply reflexes and plans, and why robots should too.

Problem and approach

I embarked upon this course of research to find a practical method of controlling walking in natural terrain. The goal was to implement and realize the advantages of walking in rough terrain. I have sought to develop robust and productive walking—robust meaning tolerant to disturbances from the environment and to errors in sensing, modeling, and predicting; and productive meaning purposeful, goal-directed locomotion with an economic balance of risk, energy, and time.

To be robust and productive, a walking robot, like any walking organism, has to produce coordinated leg motions to support and propel it in terrain that can be treacherous. To successfully negotiate natural terrains, the robot must both anticipate future conditions and immediately react to current events. Its gait should transform intentions about speed, direction and distance of travel into walking action, and during that action, it should quickly and decisively resolve events that cause minor variations in the gait.

I will describe a line of reasoning and research that has resulted in robotic walking in natural terrain, and establish that:

- Optimizing gait through planning is not practical. Progress made through these techniques has been achieved by simplifying and restricting models of the walking robot and the environment. Still, reasoning about some aspects of performance does provide useful guidance that improves productivity.
- Reactive association of sensed conditions to actions can create the fast reflexes needed to maintain a gait when destabilizing events occur. Interaction among asynchronous task-achieving processes can produce more complex patterns of action and the coordination needed for a gait. This implementation enables the robot to walk without visual perception and without explicit models. Such a system of behaviors is robust to external disturbances.
- Appropriately constructed networks of behaviors generalize to a variety of mechanical configurations and to multiple periodic and aperiodic gaits. Beyond producing fixed gait patterns, the robot can: switch among periodic gaits, spontaneously generate aperiodic free gaits, and continuously conform its actions to the underlying terrain.
- A system of gait generation can be established to enable deliberative reasoning to select and guide a gait appropriate to the perceived environment, while behavior-based control processes provide safeguarding reflexes and interact to coordinate a gait pattern.

Synopsis

This thesis is structured to build the case for a method of enabling robotic walking. Elements of deliberative reasoning, reactive and behavior-based control, and biology contribute to my approach.

Between the introduction and conclusion of this thesis are six chapters that examine the control of walking as framed in several paradigms: as deliberative reasoning, as task-achieving behaviors, and as a neuromuscular function. In each view of walking I will identify concepts that shape my approach. I have started with the objective of robust and productive walking, and have created a novel method of enabling walking.

Walking in natural terrain

I detail the problem and scope of this research: robust and productive walking by a robotic mechanism in natural terrain. I define walking and its constituent properties of standing, posturing, propelling and stepping, and limit my scope to mechanisms that maintain static equilibrium. I characterize natural terrain and motivate robotic walking in natural terrain, describing why it is the preferred method of locomotion. I pose some of the interrelated, sometimes conflicting requirements that functional walking robots must meet and that shape the form of the walking that I pursue. Then I propose that robots need an ability to foresee the consequences of certain actions, and a degree of autonomy to react to unexpected events while still executing their gait.

Planning for mobility and stability

Gait can be produced as a planning operation achieved through analytical or deliberative methods. I describe two broad areas of consideration when creating plans for a mobile, specifically walking, robot: mobility and stability.

As an instance of robot motion planning, gait planning is intractable in the worst case. Some simplification must be made to reduce complexity. I will review the results of a number of efforts to generate productive gaits, many successful with actual robots. I then describe the development of Ambler, an unusual hexapod for which planning generates walking motions and predicts stable stances before they are enacted. Ambler walks delicately in rough terrain. It demonstrates the value of planning (it foresees and avoids most obstacles) but also the difficulty of applying a plan with no run-time adaptation.

Performing patterns and plans

Fixed gait patterns that are exhibited by animals have been modeled through various methods. Using a pattern of gaits avoids many of the complexity issues in generating a gait deliberatively. But new problems arise in adapting the gait to terrain.

I develop the position that a pattern or a plan alone is not enough to ensure reasonable performance in rough terrain. During execution the robot must respond to unpredictable events and adapt its actions. This type of error detection can lead to replanning, as with the walking robot Dante I, which reactively executes its plan, modifying it on-the-fly. Error recovery, a step beyond error detection, requires fast reaction. Dante I takes the first step to detect errors in its plan but cannot always recover.

Then I look at the performance of a number of walking robots. There are few metrics of comparison and none that distinguish walking capability without regard for a specific robot. It is clear that few robots rival the capability of animals.

Walking with reactions and behaviors

Symbolic planning and reasoning can predict which gaits are feasible, but executing a precise action sequence is practically impossible. Behavior-based approaches offer a method of maintaining the character of the gait without requiring a precise description of how to walk. Several successful walking robots have demonstrated this.

I provide the principal design elements for a behavior-based gait controller that enables robust, terrain-adaptive walking, still allowing stable servo control of motions and supervisory teleoperation.

I then introduce Dante II, a frame-walking robot, and describe the implementation of its behavior-based control system and provide representative examples of Dante II's performance, including excerpts of its descent into the crater of Mount Spurr.

Generalizing behavior to multiple gaits

The biological system of controlling walking contains structures, patterns, and natural behaviors that are instructive to the development of walking robots. I will identify parallels and concepts that apply to producing gaits and also distinguish fundamental differences to see where we need artificial solutions. I will then describe how Dante II's gait control method generalizes to a more complex hexapod called SimPod. This simulated hexapod is capable of a variety of gaits seen in six-legged insects and can transition smoothly between them. Like Dante II, it can walk through rough terrain using only proprioceptive sensing.

Integrating planning and reacting

I return to the idea that there are some aspects of walking that benefit from anticipation. This suggests predictive planning operating in conjunction with behavior-based control. There seems to be growing consensus that planning and reacting can be applied to different aspects of robot control in a complementary manner. I examine some existing hybrid architectures and develop specializations for the control of a walking robot.

Behaviors provide safeguarding reflexes and embody intrinsic capabilities. I describe how they are parameterized and how plans for each aspect are made independently. Instead of planning a sequence of motions, I partition the planning problem to describe aspects of a gait for individual behaviors. I then present an implementation of deliberative planning that guides walking behavior, allowing SimPod to avoid obstacles, minimizing contact and disturbance. All its reactive capabilities remain intact; in fact, if plans are inadequate or unavailable, it still walks stably, safeguarded by its fundamental behaviors. Finally, I present results of an experiment in which the hexapod again walks across rough terrain, this time guided by independent planners which advise several aspects of its performance. This time it avoids terrain collisions and its gait becomes more productive.

Chapter 2

Walking in natural terrain

In **Walking in natural terrain** I formulate the challenge and scope of this research: the demonstration of robust and productive walking by a robotic mechanism in natural terrain. I define walking and limit my scope to mechanisms that maintain static equilibrium. I then characterize natural terrain and motivate robotic walking in it, describing why walking is the preferred method of locomotion.

Walking robots are uniquely advantageous in rough terrain because they can isolate their bodies from terrain irregularities, avoid undesirable footholds, regulate their stability, and achieve energy efficiency.

Development of functional walking robots is directed by many interrelated, sometimes conflicting, requirements. I pose some of the requirements that further shape the form of the walking that I pursue. Then I introduce a theme in this development of robust walking: that robots need an ability to foresee the consequences of certain actions, and a degree of autonomy to react to unexpected bumps and events like slips, while still executing their gaits.

Walking is self-supported locomotion

A definition of walking might be: the locomotion of a mechanism by the support and propulsion that comes from the coordinated motions of its legs.

In some ways, walking seems to be a problem of manipulation, and in some ways a problem of locomotion. It is like typical robotic manipulation tasks in that an object, the robot’s body, must be supported and positioned. It is like locomotion in that the robot is not fixed to any reference frame but is free to move throughout the world. These aspects are combined in gait, in which the deliberate manipulation of the legs results in locomotion.

Walking can be statically or dynamically stable. Statically-stable robots maintain static equilibrium throughout their motion. This means that at all times the robot is supported by at least three points of contact, and that those contact points enclose the robot's center-of-gravity. Statically-stable robots must have at least four legs (since one leg has to step, while three support), but commonly have six. The condition of static equilibrium also restricts speed, since cyclic accelerations must be limited in order to minimize inertial effects. [McGeer90] Some mechanisms are referred to as dynamically-stable. [McKerrow91] These mechanisms are not in equilibrium at every instant, but their legs strike the ground and apply restoring forces, or they accelerate their bodies such that inertial effects provide the necessary balancing moments. [Takanishi90]

My research has concentrated on scenarios in which slower statically-stable locomotion is applicable, and high speed is unnecessary or dangerous. Static stability enables slow, smooth motion, complex body motions, and flexibility in the placement of feet. I will limit the applicability of this thesis to robots that maintain static equilibrium.

Aspects of statically-stable walking

Just as an animal must stand before it can walk, there is a logical ordering of the capabilities of a walking robot. It must stand before it can posture, posture before it can step, step before it can propel, and propel before it can walk.

Standing is the act of maintaining a stable base of support. It simply involves keeping sufficient feet on the ground to maintain static equilibrium. Although standing might be considered a static condition, it necessarily involves resisting dynamic disturbances that might change the condition of the feet, as when footholds crumble away. The principal challenge in standing is to keep enough feet on the ground, supporting the body while outside forces are acting on it.

Posturing is the act of adjusting roll, pitch, and elevation. This is different from standing; it involves adjusting leg extensions to maintain an appropriate posture. As a robot walks it may have to adjust its orientation (roll and pitch with respect to its frame of reference) to stay level or at least to maintain its center-of-gravity within its support legs. External forces may be substantial enough to affect the robot's stability, so corrective motions are an integral part of walking.

Propelling is the act of moving laterally, longitudinally or rotationally (in yaw) with respect to the feet. To propel, the robot must translate its body (center-of-gravity) from its base of supporting legs to a new base, all while maintaining posture. Posturing and propelling together encompass the six degrees-of-freedom of the robot's body with respect to the world. A robot, if it is able to stand and actively control its center-of-gravity by posturing and propelling, can selectively eliminate legs from the essential supporting set. Those legs are then free to move to new locations—to step.

Stepping is the act of lifting a foot from ground contact, transferring it to some location, and placing it in ground contact again. Stepping involves selecting an appropriate leg (perhaps by following a pattern but also by deliberate reasoning), identifying an appropriate foothold, and joining these two with a trajectory through free space. The foot breaks contact with the terrain, moves from one location to the next, like a manipulator, and then touches down in controlled impact.

To expand my definition of walking, observe that it is the collective result of standing, posturing, propelling, and stepping. A stable coordination of all these leg motions is a gait—and walking is the application of a gait. *Walking* coordinates the standing, posturing and propelling action of a group of supporting legs with the stepping action of recovering legs, and appropriately exchanges supporting and recovering legs to produce locomotion.

Walking is uniquely suited to natural terrain

What is natural terrain?

Natural terrain is geologically constructed—it is not artificially shaped, cleared, or leveled, but is a varying contour of mountains, hills, valleys and ravines. Particles of sand, soil, gravel and rock form the aggregate. These constituent materials have differing cohesive properties and those properties change as water content turns the ground from dust to mud. In some places material is piled at its angle of repose, and in other places it is in smoother rolling hills, but rarely is natural terrain flat.

Natural terrain is often densely populated with semi-discrete obstacles: geologic features and individual rocks, and vegetation such as trees, bushes, grasses and moss. By natural terrain I mean the areas that have not been structured or constructed artificially: the forests, fields, mountains, shores and seabed. The surface of Mars, as seen in Figure 2-1, is an example of rough natural terrain. [Murray81]

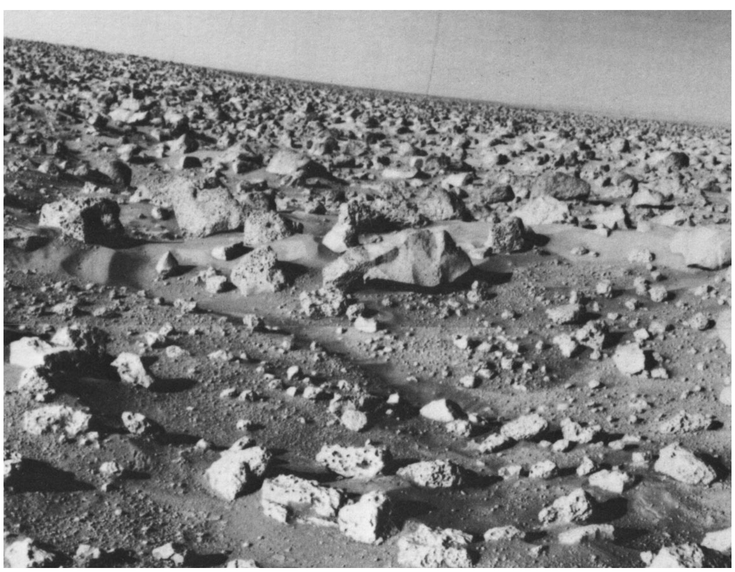

Figure 2-1: The terrain around the Viking 2 landing site on Mars is strewn with rocks believed to be distributed by meteor impacts. The underlying sand is fine and unconsolidated. Rocks range in size from a few centimeters to 25 centimeters (bottom right corner) to over one meter (largest at center). The horizon is 3 kilometers distant and level; its apparent slope is due to the tilt of the lander.

How walking is better than rolling

There are many ways in which walking and rolling differ. The conclusion made most apparent by these differences is that it makes sense to walk on rough terrain, but roll on hard, flat surfaces. By some estimates [Raibert86], more than half of the Earth is inaccessible to wheeled mechanisms (including tracked mechanisms, which behave like wheels of large diameter [Bekker56]).

Feet make discrete terrain contacts

Feet make discrete terrain contacts, footholds, while wheels propel with continuous rolling contact. A wheel interacts with a greater amount of terrain than a foot does, so more of the surface must be fit for traverse, and it must lie in a continuous path. [Hirose84] In terrain strewn with obstacles like rocks, a series of discrete footholds is more available than a continuous path. As the density of obstacles increases, continuous rolling contact with the terrain becomes more difficult. [Bares93]

Footholds can be optimized

Because feet make discrete terrain contacts, it is possible to avoid undesirable footholds such as locations that are unstable, on the edge of an obstacle, too soft or too hard. It follows that footholds can be chosen because they improve stability or affect body posture.

Environmental impact is reduced

Legs propel with static rather than rolling friction, so they impart smaller tractive forces on the terrain. Typically footholds have less total contact area than tracks, which results in less disturbance. The instantaneous contact area is generally larger for a foot than a wheel, which results in lower ground pressure. These three factors all imply less force imposed, and consequently, less deformation of the terrain. In sensitive enviroments like wetlands and tundra, this reduced impact may be desireable.

Posture is terrain independent

The posture of most wheeled mechanisms is dependent upon the terrain, meaning as the terrain pitches and rolls so does the wheeled mechanism (assuming it does not have active suspension). On the other hand, legged mechanisms that actively posture can isolate their bodies from the terrain, so they achieve more smooth, level motion. Terrain-independent posture boosts energy efficiency. It also improves mechanism stability, which in turn affects the quality of sensing it can produce and the types of payloads it can carry.

Omnidirectionality is possible in natural terrain

Omnidirectional motion is available to any mechanism with three degree-of-freedom legs. [Waldron85a] Wheels must overcome their inherent directional bias to achieve omnidirectionality.

Body-scale obstacles can be crossed

Walking robots can surmount body-scale obstacles because they step over, step onto, or climb obstacles without requiring the large tractive forces of rolling. [McGhee79] Wheeled robots that try to surmount obstacles larger than the wheel radius must produce large tractive forces to lift the mechanism over the obstacle.

Walking in rough terrain is theoretically energy efficient

Theoretically, walking requires less power than rolling because body motion can be gravity-decoupled and because propulsion is by static, not rolling, friction. Walking in the gravity-normal, level plane—when achieved—conserves energy typically lost as the mass rises and falls with the underlying terrain. Rolling propulsion results from thrust against a surface. If the surface is held together by cohesion, like soil, then energy is expended in tractive compacting, bulldozing, and otherwise transforming the surface. [Bekker56] Walking machines compact only discrete locations, thus expending less energy. [Todd85] On hard, flat ground, wheels are more energy efficient and faster than legs, but as cohesion and smoothness decrease, increasing wheel size and power are required to achieve the propulsion produced by the same foot. [Bekker61] On soft natural terrains, only relatively large wheels could perform as well as a foot. In practice, the reciprocating motion of walking requires so many moving parts that internal losses dominate the apparent energy efficiencies.

Robots must satisfy conflicting requirements

Robots, in both their design and operation must satisfy many, sometimes conflicting, requirements. For walking robots, these conflicts can be quite acute, like the direct conflict between maximizing velocity and stability, which alternately argue for large and small motions. How these requirements are met is partly defined by the method of generating gait, and impacts the nature of the gait that results. One categorization of requirements is into performance, configuration, task, and operation. I will describe requirements in each category as a way of describing the breadth of issues faced in creating a practical method of generating gait.

Performance requirements

A robot should address certain economic considerations. It should perform its task, while minimizing risks to itself and its environment, the energy it consumes, and the time it requires.

While walking the robot must remain stable by sensing orientation and forces, and assessing the influence of terrain and subjective risks. It seems prudent to maximize stability, but this often conflicts with maximizing mobility.

The unique advantage of walking is superior mobility in rough terrain. To exploit this advantage, the walking robot should seek maneuverability and flexibility within limits of its physical dimension, configuration and power.

How fast the walking robot must go can be of paramount importance. If it must achieve high speeds, if it must run, many other considerations and capabilities necessarily fall by the wayside because of the lack of available time. Even if the robot remains statically stable, speed has an impact as a slow creeping wave becomes a fast tripod gait.

Configuration requirements

There are often conditions that constrain the physical configuration and resources available to a walking robot. For example, extraterrestrial explorers are necessarily low in weight and power because of the extreme cost of transporting the robot and its fuel into space. Size and power requirements impose a systemic constraint on the robot, dictating what sizes of obstacles will be surmounted. This in turn affects the control strategy—smaller size and power may lead to more obstacle circumnavigation.

Robots that interact with a partially unknown or unstructured environment need to sense. To produce controlled actions, robots at least have to know their joint positions and, perhaps, the forces imposed upon them. They may also need to sense their surroundings. To model, or just to perceive and react, brings up many sensing issues including modality, resolution, frequency, accuracy, precision (repeatability) and deployment. How the robot senses, proprioceptively and perceptively, affects gait control. For example my research relies on contact sensing in the robot's legs.

Particular types of actuators—pneumatic, hydraulic, electric, or even muscular—impose demands on the walking robot. They limit performance, define configuration, and affect how walking tasks are achieved, whether the actuators can be controlled precisely (for example, by closed-loop feedback) or crudely. Complementary actuation, for example a tether to assist sloped climbing, offers advantages but also places certain demands on the gait, in this instance to minimize turning (to avoid lateral strains imposed by fighting the tether).

Task requirements

The type of task the robot must perform affects the method by which it produces gait. A walking robot intended for indoor use must be adept at conforming its gait to such features as stairs, doorways, and rectangular turns. Outdoors, rough terrain, discrete obstacles and irregular patterns may demand a more adaptive gait.

The task may involve a certain degree of purposefulness in the robot's actions. Is the robot strongly goal-directed, willing to risk survival to arrive at a destination, or is it able to wander and perform a useful function while avoiding difficult and dangerous challenges? If the robot has a destination, it must somehow navigate. The fidelity with which the walking robot can track a specific path has implications to how and whether it performs localization.

What type of terrain will the robot encounter? Certainly it must perform on flat terrain but the challenge lies in rough terrain. How big are the obstacles; how steep are the slopes; how soft is the soil? These factors impact the scale and relative properties of the walking robot. Since it is the unique advantage of legged mechanisms over wheeled or tracked alternatives, it makes sense that walking robots must demonstrate their capability in rough terrain.

Operator requirements

Teleoperation is exhausting; centralized autonomy is impractical; yet supervisory control is critical and coordination is crucial. How is control shared between the robot and human operators? Is the robot completely autonomous; does it share control with the operator, receiving guidance and directives; or is directly teleoperated with no intrinsic capability?

Is the robot observable, and what is the extent of sensory feedback to the operator? If the operator cannot determine what the robot is doing, teleoperation is impossible; alternatively, if the remote environment provides fully-immersive telepresence, then teleoperation may be appropriate. Communication-related issues regarding available bandwidth, latency, and continuity affect the control mode.

Walking robots need autonomy

I will make an assumption, explain it here, and justify it through the course of this thesis. The assumption is that walking robots need some autonomy. A robot that can independently and intentionally produce actions is autonomous. Its autonomous capabilities may include some, but not necessarily all, aspects of what it does; this is sometimes referred to as limited autonomy. Autonomy is needed for the automatic actions fundamental to walking. There are at least two reasons for this: the complexity of motions defies direct teleoperation, and the likelihood and timescale of disturbances require fast automatic reaction.

Autonomy is needed for supervisory teleoperation

Some functions of a walking robot have to be automatic because direct teleoperation is impractical. To directly teleoperate, the operator must coordinate and command many individual motions, and respond to dynamic events that occur while the mechanism walks. A substantial amount of information is needed to be fully aware of the robot's situation, but bandwidth and latency usually limit what an operator can receive quickly. A person teleoperating a walking robot has to process all this information, and react as quickly as the robot can move. Indeed, if there is latency in the communication the operator must anticipate and react even faster, so some functions must occur onboard, automatically.

Sheridan has observed that the delay in supervisory control is acceptable if subgoals are conveniently large, unpredictable aspects of the environment are not changing too rapidly, and the subordinate automatic system is trustworthy. [Sheridan92] What the autonomous capabilities of the robot must do is coordinate motions, respond to rapidly evolving events, and provide the robot with fundamental safeguards.

Autonomy is needed to react to unpredictable events

The notion of fundamental safeguarding is important to enabling supervisory control, but more critically, it addresses the fact that even a slow, statically-stable walking robot experiences sudden destabilizing events. Legs collide with obstacles like rocks and undulations in the surface; the ground compresses or crumbles away, tipping the machine. These events are expected, but when they will occur cannot be predicted. The walking robot must be able to respond immediately, as a reflexive action, to survive.

Summary

- Walking requires the ability to stand, to move the body through posturing and propelling motions, to take steps while resisting external disturbances, and then to coordinate these motions into a gait.
- In natural terrain, walking is well-suited because feet avoid undesirable footholds and make discrete, select terrain contacts. Legged mechanisms surmount terrain discontinuities without requiring large tractive forces, and can isolate their posture from the terrain, minimizing required power and maximizing stability.

- Walking robots should succeed where they are most applicable, in natural terrain. This involves conflicting demands of physical configuration, task and operation, all of which affect performance and the method by which it is achieved.
- Autonomy is a necessary attribute of any walking robot. As a robot walks, its forceful interaction with the environment causes rapidly evolving events like bumps, slips, and tips. Reactions faster than a human operator can provide are needed for its survival.
- The scope of this research encompasses statically-stable walking robots operating in rough natural terrain. This thesis develops methods to impart robust and productive capability and autonomy in real robots operating in real terrain.

Chapter 3

Planning for mobility and stability

In **Planning for mobility and stability** I examine the production of gait as a planning operation achieved through analytical or deliberative methods. I describe two broad areas of consideration when creating plans for a mobile, specifically walking, robot: mobility and stability.

As an instance of robot motion planning, gait planning is intractable in the worst case. Some simplifications must be made to reduce complexity. I will review the result of a number of efforts to generate productive gaits, many successful with actual robots. I then describe the development of Ambler, an unusual hexapod for which planning optimizes walking motions and predicts stable stances before they are enacted. Ambler walks delicately in rough terrain. It demonstrates the value of planning (it foresees and avoids most obstacles) but also the difficulty of applying a plan with no run-time adaptation.

Planning optimizes mobility and stability

There are many kinds of plans, and models of what planning is. And there are many philosophical arguments for what a plan should be and how it is best created. The form the plan takes depends on how it is used. [Agre90] Ultimately a plan is something—a schema, a potential field, an action mapping, a policy—that dictates actions. Actions are planned to be stable and efficient and to optimize motions to minimize risk, energy and time. For walking robots, plans generally come down to sequences of actions which become servo references to move actuators in a coordinated manner.

There are two broad areas of consideration when creating plans for a walking robot: mobility and stability. Mobility considerations ensure continual motion and maneuverability, while stability constraints maintain static equilibrium and position the robot to resist disturbances.

Planned motions have to be generated that move the robot's limbs to positions that enable it to propel the body along a prespecified path. Presumably, the path is well-chosen and the robot must find a means to move along it. Mobility is influenced by two factors: the physical limitations of the environment, and those of the robot itself. As a walking robot moves along the desired path it cannot let its flexibility of motion compromise its stability. The planning problem also involves avoiding those stances that are not statically stable, and trying to find the most stable sequences of actions.

Which is more important—stability or mobility? The answer depends on many conditions, for example the trade-off between speed and stability; a plan has to satisfy, if not optimize, these conflicting demands.

Considerations of complexity, representation, and reasoning

Planning gait for a walking robot is certainly an instance of motion planning and as such, shares common considerations. An appropriate method to represent the problem and then a way to reason an appropriate solution is far from unanimous, and worse, is probably intractable.

Gait planning is intractable in the worst case

The *generalized movers problem* encompasses the task of moving a general robot, an arm or mobile robot, in a three-dimensional environment filled with obstacles. To plan a trajectory for the robot—position as a function of time—an algorithm must take into account the physical limitations of the robot and economic (available time) considerations, which often mandate the minimization of such things as the time duration or energy expenditure. The problem of planning the gait, the position of legs as a function of time, naturally fits into the framework of the generalized movers problem.

The generalized movers problem is NP-hard, which is to say that in the worst case exponential time may be required by any algorithm that solves the problem. Further, it is nonpolynomial in space and time complexities—even with an unlimited parallel computer, the problem may still require exponential time. [Canny88] In the worst case the gait planning problem is, by inference, intractable.

Canny showed that the general robot motion problem can be solved with complexity singly-exponential in time with the exponent equalling the number of degrees of freedom. For a three-link, fixed manipulator the algorithm is $O(n^3 \log n)$ where n measures the number of obstacle vertices, edges and faces. For many problems this is quite workable. For an 18 degree-of-freedom walking robot (able to translate and rotate in 3 dimensions), the algorithm is $O(n^{24} \log n)$ which is quite unworkable.

There are several ways of treating a problem that is intractable in the worst case. Sometimes it is no problem at all; for example, the simplex algorithm for linear programming has exponential time complexity, but in practice runs quickly, never approaching the worst case. There is little reporting of discoveries in motion planning that provide reasonable best case performance. Latombe and colleagues have had some success with high degree-of-freedom systems and with the coordination of two manipulators.[Latombe91][Latombe92] But tractable methods of coordinating 18 degree-of-freedom motion, much less coordinating six manipulators, as legs could be considered, is not forthcoming. More typically, heuristics can be exploited to simplify the problem. Of course, this voids any guarantee of optimality.

On the basis of the complexity of gait planning alone, it is apparent that a general, optimal solution is probably intractable. Progress must lie with these satisficing solutions.

Using representation and abstraction

Only recently has much progress been made using configuration space representations of high (greater than 8) degree-of-freedom mechanisms. [Barraquand89][Latombe92] As mentioned, the complexity of the motion planning problem, and by inference the gait planning problem, is exponential in space as well as time. A complete construction of a configuration space is therefore impractical. [Latombe91]

Madhani has developed a configuration space representation of a six degree-of-freedom climbing robot. [Madhani92] This formulation, which does not run in real time, is able to resolve configuration constraints on three legs as they climb inside pipe.

Most work on gait planning does not apply a configuration space representation, but instead describes the robot by its kinematic parameters. In cell-decomposition methods the number of cells generated is a polynomial function of the number and degree of the constraints used to model the robot and obstacles.

Global methods may also be intractable for higher degrees-of-freedom if they represent the connectivity of free-space as a graph, which requires exponential-time precomputation. Local methods that apply, for example, potential fields are troubled either with local minima or with excessive computations to eliminate all but the global minima.[Barraquand89]

Although path planning is theoretically well understood, current methods are not practical for more than four degrees-of-freedom. With more than four degrees-of-freedom, applications are limited because techniques are not complete—they may fail to find a solution in even simple settings. Some high degree-of-freedom problems can be solved with Monte-Carlo techniques if the large search spaces of these problems are associated with large subsets of good suboptimal solutions. [Barraquand90]

These variables have a restricted range of valid assignments. Some, often many, of these variable ranges are dependent. In any given situation, there are few motions worth considering (only a few dimensions of the state-space are relevant). The trick, of course, is knowing which subspaces will contain the optimal (or satisfactory) motions.

Another sometimes complementary representation is to plan the cartesian locations of the feet relative to some robot-centered frame of reference. [Hirose84]

In cases where the environment is represented as other than flat and obstacle-free, a discretization of admissible and inadmissible cells is common. [Hirose84][Kwak88] [Jeong95a] A few systems have gone beyond this to consider topography. [Miller92] [Krotkov94]

Inductive and deductive reasoning

Planning problems are often formulated as an initial state, a set of one or more goal states, and a set of state-transforming operators. The collection of states and operators is referred to as state-space. The operators have preconditions that define where they can be applied (which states they can transform) and postconditions that describe the result of the operation.

Gait planning has been formulated in this manner: the robot position is known, the world is known, and the goal is known (although typically it is partially defined, such as the body position is known, but not specified are the orientation or the positions of the leg joints). Motions transform the robot from one state, one stance, to another.

Forward chaining, applied to gait planning, begins with the initial state and adds atomic actions (evaluating each for progress toward a goal) until the goal is reached. This works inductively with an exhaustive generate-and-test of possible actions but usually involves optimizations that reduce the number of cases that must be considered.

Backward-chaining begins with the goal and arrives at the initial state by deduction. This is difficult because the goal from which backward chaining might work is ill-defined. It may be clearly defined in 6 dimensions, those of position and orientation, but it is seldom known in the additional freedoms of the leg, which is to say that the precise foot positions that put the body at the goal are not known because there are usually a set of equally acceptable possibilities. This set of successful goal stances chains backward one ply to an even larger set of stances.

Approaches such as binary search techniques which look for a subgoal intermediate between the initial and final positions are troubled again by the impossibility of selecting from a combinatorially exploding number of acceptable but suboptimal intermediate goals.

A deductive approach has been successful in selecting an appropriate gait pattern, [Choi88] and in determining which leg to move, one step at a time, [Kwak88] but never in producing a complete action sequence.

So induction is the common approach to planning and because it works forward, it suffers from the horizon effect which becomes most apparent when deadlock occurs. When the robot steps into a configuration from which it cannot proceed because lifting the next leg would violate static equilibrium, it has become deadlocked. Hirose described deadlock as the condition in which a leg must be lifted to make forward progress but lifting that leg leaves the center-of-gravity unsupported. [Hirose83] If there is any dynamic component to the gait, for example if inertia keeps the center-of-force within the support polygon, then the robot may truly be stuck. More likely it must reverse several moves in order to proceed. To avoid deadlock, some solutions have been posed. [Ding94] Most rely upon establishing strict periodic constraints (fixed gaits) to avoid limiting legs.

Methods of planning gaits

To solve the gait planning problem, simplifications have to be made to reduce complexity. Various researchers have addressed this by simplifying the capabilities of the walking robot or by restricting the environment (assuming either a flat terrain or precise knowledge of the terrain).

With these simplifications, three types of solutions have been applied: analytic derivation of an appropriate plan, searching a limited space of possible motions for an acceptable sequence, or using analytic methods to restrict the set of possible motions and then searching to identify a satisfactory solution.

Deriving gaits analytically

By identifying a set of principles, Hirose designed a hierarchy of rules that limits possible leg moves and generates a free gait with smooth body motion and terrain-adaptability for a quadruped mechanism. [Hirose84] That quadruped could use a *crab* gait. An analysis to determine the optimal *crab angle* for any given stance of a quadruped and to identify turning gaits further improved performance. [Zhang89]

Boissonnat considered an instance of the motion planning problem for a legged robot. The problem of reaching acceptable footholds was formulated with Voronoi diagrams, and stability was ensured through a validation of body placements. The solution is nonoptimal and does not bound the number of leg moves, but is complete in that if a solution exists, it is found. [Boissonnat92]

Turning gaits (or more specifically spinning gaits which involve rotation with no translation) have been treated as both periodic and aperiodic patterns. Both Zhang and Jeong have proposed analytic methods of solving for the proper leg sequence of spinning gaits. [Zhang91][Jeong95b] Both solutions assume unobstructed, flat terrain.

Searching for appropriate periodic gaits

Planning can be described as rule-based if its operation is to identify a condition and apply a rule to increase or decrease the abstraction of the condition. Production systems and other techniques may be applied, but the essential function is to transform information up and down a control hierarchy of tactical and strategic planning. For example, a rule-based gait planner might decompose the speed of advance to applicable periodic gaits, or abstract a terrain obstacle to the class of trenches the walker can cross. Both the selection of gait and the adaptation of individual moves have been implemented by the application of rules.

Kumar developed a number of strategies to modify gait parameters, such as the stepping rate and the amount of support time per leg, to optimize a wave gait for a given path. [Kumar89a] Transitions between gaits, because they are usually aperiodic, are a problem for this approach. In another planner, to adapt to somewhat irregular terrain, the stepping sequence remains constant, but specific foot placements are adjusted. [Qiu89]

In this selective approach, a specific gait pattern is selected and then individual moves are modified through a prearranged decision process. A collection of periodic gaits is predetermined, and one gait is applied for each type of terrain obstacle. Periodic gaits are reliable and stable. They can be very efficient, even optimal, in their target environment. Most of the time, a walking robot can successfully apply periodic gaits and it will be productive and robust. However, in rough, irregular, or complex terrains, fixed gaits that do not fully adapt to the environment are insufficient and the walker must resort to generating a free gait.

Searching for actions to construct aperiodic gaits

There are two basic problems with searching state-space for an optimal gait: its size and its horizon. The space grows exponentially with the number of constraints and with the number of degrees-of-freedom in the robot. The search can be kept manageable by considering limited leg placements for each body move, however this compromises the optimality of the resulting gait.

No unbounded search can escape the horizon effect. However, for most legged mechanisms, some finite number of *gait cycles* is sufficient to reconfigure to any arbitrary stance. Often searching beyond this depth ensures that no dead ends will be encountered. Whether to look ahead in planning or to execute and then backup (and how much) remains an open question.

Pal has constructed a search space by discretizing the local (leg workspace) and global (terrain) reference frames. This space can then be searched for possible leg and body move sequences that progress toward the goal. By using the A* algorithm, the optimal gait can be found in the search space—a very simplified world with restricted leg placement. [Pal90][Pal91]

Increasing a robot’s degrees-of-freedom allows more complex gaits. In high degree-of-freedom mechanisms the sequencing of the gait pattern, as well as the characteristics of individual moves, is a variable and the gait need not be periodic. Periodic and aperiodic gaits are subsumed by *free* gaits in which any leg is permitted to move at any time. [Kugushev75] In smooth terrain, a walking robot’s gait should degenerate to a periodic gait because of the provable optimality in terms of speed and stability.

An important advantage of allowing a free gait is that it can be optimized to a specific situation. To generate the most robust gait, the optimization must be situation-specific and occur during operation. McGhee developed a hexapod device and a free-gait-generating algorithm that found reachable stances by exhaustively searching from the kinematic limits of the current stance. [McGhee77][McGhee79]

Rule-based coordination of free gaits in a terrain with some inadmissible regions was demonstrated by Kwak for hexapod configurations like the ASV. [Kwak88][Kwak90] The ASV employs an alternating tripod gait, which is not well suited to terrain conditions in which areas under some legs are unsatisfactory for load bearing because failure of a single supporting leg will destabilize the robot. The motion coordination rule set independently controls each leg with a leg plan machine, control machine, executor, contact sensor, foothold finder, and calculator.

Recent research into robotic walking has shifted from optimization based on static stability to construction of action sequences with more consideration of foothold selection—static stability is a constraint, but it is one of many that must be considered and satisfied. Constraint-based approaches to gait generation utilize various factors such as kinematics, terrain elevation and stability to constrain the range of possible moves and then order the remaining moves so that search or optimization can be used to create an applicable free gait. In any situation, if a gait exists it can be found, and if multiple gaits exist, efficiency, stability or other objectives can be optimized. Constraint-based planners have the advantage that they can consider a wide range of possibilities both in the motions of the walker and in the objectives they will pursue.

Often so much deliberation is required that the constraint-based planner cannot quickly react to its environment.

Ambler, a circulating-gait hexapod

Ambler is a hexapod walking robot that uses analytic methods and search for its gait planning.

An Earth-based prototype

Ambler's design objectives were to demonstrate extreme rough terrain locomotion, extended autonomy, and relevance to the power, distance, and scope of an exploration mission to Mars. These criteria resulted in an unusual and large configuration to overwhelm obstacles and carry large payloads, but slow in order to conserve power and to practice extreme conservatism in stabile, delicate walking. Ambler, seen in Figure 3-1, is designed for a stable traverse of slopes up to 30° with frequent one meter magnitude surface features such as ditches, boulders, and steps. [Bares89][Krotkov92]

Figure 3-1: Ambler outside on rolling, grassy terrain. During this walk, Ambler set its endurance record, traveling 527m horizontally and 25m vertically (slopes to 20°) in 1219 steps over a 21 hour period (0.4m/min).

Ambler is an Earth-based prototype, so other Martian environmental factors, such as temperature, are not addressed.

Unique orthogonal legs

Ambler is supported by six legs, each consisting of two links in the horizontal plane, one rotational and one extensional, and one extensional link in the orthogonal (vertical) plane. The horizontal links permit planar motion of the leg and body while the vertical extensional link provides the ground contacting motion of the foot. The rotational links, which are stacked concentrically with three legs on each of two shafts, are able to rotate fully around the body. The orthogonal legs provide a relatively large space of possible footholds, making Ambler more maneuverable, but increasing planning time. This orthogonal leg arrangement reduces the power required for locomotion by limiting propulsion to a level plane so that no energy is expended changing the height of the center of gravity.

Ambler walks with a circulating gait

Ambler walks by lifting a leg vertically, swinging it in the horizontal plane, extending it down to terrain contact, and then gliding the body forward at level elevation, coordinating actuation of the supporting legs. Ambler can perform any of the gaits associated with hexapods including the wave, rachet, and tripod gaits. However, its primary gait is a *circulating* wave, because it is the most productive gait available to the Ambler configuration.[Bares90] The circulating wave gait, which has no natural counterpart, is performed by lifting a rear trailing leg, passing it between the stacks, and placing it out in front of a leading leg. After repeating this sequence, the final foot positions are the same as a rear-propagated wave gait, but only one leg has moved. Recently, Pai has developed a tumbling gait for a tetrapod which is also a circulating gait; a single leg recovers over the body as the tumbles forward. [Pai94] By circulating one stack forward and one stack backward Ambler can turn in place. When necessary, Ambler can resequence leg motions into a free gait. Through proper adjustment of leg strokes, Ambler can follow an arc of any radius from zero for a point turn, to infinity for a straight line. It can perform crabbing gaits laterally or at any crab angle by forgoing its circulating motion and freely repositioning the legs.

Detailed terrain sensing and modelling

Since Ambler applies a hierarchical model of composing sensing into models and then decomposing plans into commands, a rich collection of sensors creates the requisite basis for model building. [Lin90] Ambler has absolute position encoders on all joints. In the rigid ankle of each foot is a six-axis force/torque sensor.

Ambler uses a laser rangefinder with sophisticated tuning and filtering to produce high-resolution elevation maps. Kweon developed and Krotkov has extended the elevation mapping technique that produced a continuous topographic map from range-sensor data. [Kweon90][Krotkov94] It merges maps acquired over time and builds an extensive representation of its surroundings. This process is time and data intensive.

Mobility is geometrically constrained

I define mobility as the robot’s capacity for changing its position, or the position of its constituent motions. A measure of mobility is the number of feasible configurations within some limited distance of the current configuration-space position. Geometric constraints on mobility come from the robot and its environment—both the current and future kinematic configurations of the robot and the terrain it is in.

Identifying and modelling geometric constraints

Kinematic configuration of the robot

The robot's kinematic limits constrain its mobility because legs can only step and propel within these limits. The kinematically accessible area is further limited by the intrusion of other legs. Walking robots commonly have overlapping leg workspaces, so avoiding contact between two legs limits the placement of some feet.

Terrain and external obstacles

The terrain presents obstacles of height, width, and configuration. Plans for walking robots need to account for the height of leg recovery and the height of support. They need to specify the width of stride and plan body motions to allow access to specific footfalls.

Bajcsy has developed procedures to determine the material properties of terrain (penetrability, compliance, surface roughness) with the feet of a walking robot so that it can sense variations in terrain properties and avoid sinking, slipping, and falling. [Bajcsy92] Similarly for the Ambler, Nagy [Nagy91] studied traction and Caillas [Caillas89] developed measures of terrain roughness. These characteristics can be combined in an ad hoc manner (for example [Hsu91], in which a weighting is learned from operator-perceived preferences) to further constrain potential motions.

Maneuverability in the future

It is also possible to constrain mobility by considering the effect of leg placement on future motions. For example, it is not usually effective to place a leg immediately in the path of the body.

Leg and body motions are not independent. The motion of a leg is constrained by the achievable motion of the body, and the motion of the body is constrained by the possible motions of the legs. For example, lowering the body to step down into a ditch or selecting higher footholds to allow the body to rise over an obstacle requires a combination of moves found only by planners that can look ahead. Incomplete reasoning about the relationship between leg and body moves can lead many planners to overlook acceptable gaits. This deficiency is inherent in any non-exhaustive consideration of possible motions. For practical purposes, some search space pruning that eliminates contorted unproductive motion sequences while leaving productive moves provides sufficient plans in the vast majority of situations.

Mobility constraints for Ambler

Kinematic constraints ensure motions will remain within physically realizable limits. Feet must be placed within kinematic limits of the leg, the *leg reachable space*, shown for the left leg stack in Figure 3-2. The minimum and maximum extensions of the legs limit the body motion. For Ambler the abstraction *stack reachable space* simplifies the selection of rotation and translation. Each stack must be maintained in its respective reachable space. The webbed-foot shaped regions (shown shaded grey in Figure 3-3) are kinematically feasible, based on the established leg placements.

The stack reachable space is constructed as follows: for each supporting leg on a stack, the reachable space of the stack relative to the foot is determined (this is any location of the stack that would allow the specific foothold); these spaces are then intersected to

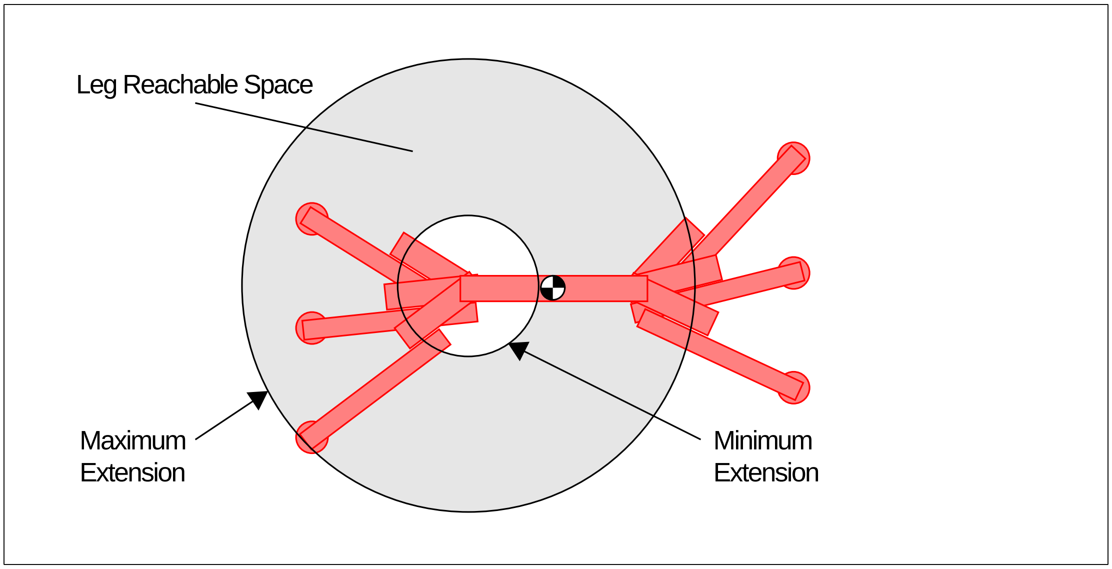

Figure 3-2: The leg reachable space for Ambler is the shaded region. It can be reached by any leg on the left stack. A complete, free-gait planner must consider every location in this region as a possible foothold.

define the region in which the stack must be to allow the feet to remain in their footholds. Any translation and/or rotation that maintains each stack in its respective region is allowable.

Because Ambler's legs rotate around two stacks, it is natural to think of constraining the position of each relative to its associated feet. This has the effect of also constraining Ambler's rotational motion. The same is true of any walking robot in which the position of any two points affixed to the robot's body are constrained relative to groups of feet.

By accurately modeling the walking mechanism to determine the positions at which internal collisions between two legs (or between a leg and the body) occur, those steps that cause collisions can be eliminated from consideration. The collision constraint is particularly important when the robot is in an irregular stance—it generally governs body motions for very small radius turns where self-collisions predominate. In practice, determining collision constraints is surprisingly difficult and requires careful calibration and experimental testing.

Terrain constraints are used for making terrain contact with the feet and avoiding terrain contact with the legs and body. With a model of the terrain, in Ambler's case a regularly gridded height field, footholds that are on the terrain and within the limits of the maximum and minimum vertical travel of the leg are identified. Leg and body moves are scrutinized at fine resolution to ensure that no terrain collisions occur during their entire planned motion.

Stability ensures static equilibrium

Identifying support and stability constraints

The support pattern for a stance is the minimum bounding polygon on the ground plane that includes all leg-ground contact points. As long as the projection's center-of-gravity intersects within the support polygon, the robot will remain statically stable. [Song87]

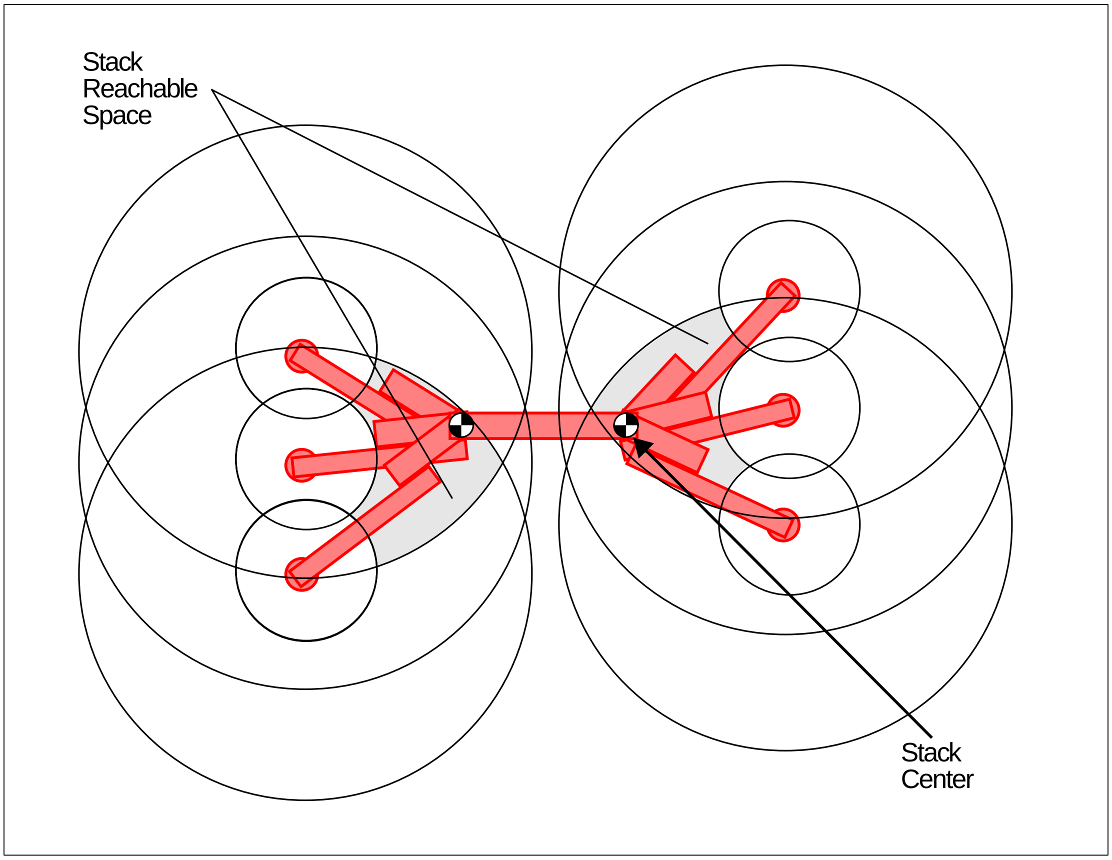

Figure 3-3: The stack reachable space for the Ambler is a composite of the six leg spaces. Translation and rotation are restricted to maintain the center of each stack within their respective shaded region. This simplifies the planning of twelve degrees-of-freedom to three.

Mahalingam proposed the conservative support polygon as a further constraint to restrict the position of the center-of-gravity so that any leg could fail and the robot would still be supported. [Mahalingam89]

Stability metrics provide a measure of the relative stability of different body postures for a given constellation of feet. To resist the forces encountered while walking in rough terrain and to distribute forces among the legs, stability is essential. [Klein87][Klein90] As it applies to a walking robot, energy stability is a measure of the energy required to overturn the robot. It can be used as a threshold to eliminate unstable stances from consideration, as a comparison among a group of prospective stances, and in optimization to select the most stable sequence of stances.

Nagy proposed several extensions to the energy stability margin. [Nagy92a][Nagy94] He suggested that non-supporting legs can contribute to stability—dragging your feet can be good. This metric considers foot sinkage and the projection of non-supporting legs onto the ground in the event of tipping.

Stability constraints for Ambler

Support constraints distinguish stances that are statically stable. The support polygon and conservative support polygon are geometric constraints used to select body moves, and projecting the implications of these constraints into the future, they limit the leg moves to those that maintain walker support.

The support polygon is the convex hull of the walker's supporting legs. If one supporting leg fails, either due to mechanical failure or soil collapse, the support polygon is reduced to the convex hull of the remaining legs. Considering the potential failure of each of *n* supporting legs leads to *n* possible support polygons. The common intersection of these polygons is called the *conservative support polygon* (CSP). When the projection of the center-of-gravity is within the CSP, support is guaranteed even if any single supporting leg fails. [Mahalingam88]

As an example, with Ambler's six legs in contact with the ground during a body move, the CSP is generally a quadrilateral as shown in Figure 3-4. With only five legs on the

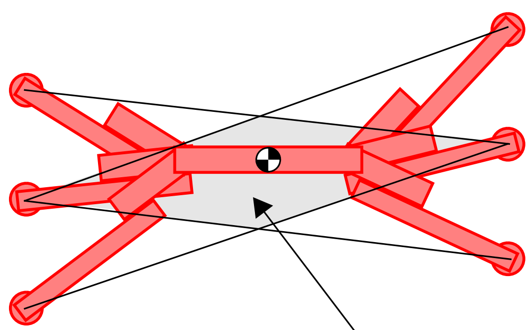

Figure 3-4: Conservative support polygon with six supporting legs. If the center-of-gravity remains within the diamond-shaped region, any leg can fail and the robot will still be supported by the remaining legs.

ground, as during a leg recovery, the CSP is reduced but still allows adequate body translation.

The CSP abstraction is useful in the planning process because it provides limitations on the movement of the body and on the footfalls that should be considered. The body must stay behind the leading boundary of the CSP, thus a feasible gait sequences moves so that the body glides from one CSP to the next. Again, the planner's ability to look ahead is important.

Energy stability was defined by Messuri and Klein as the minimum energy required to lift the center-of-gravity of the robot over an edge of the support polygon. [Messuri85] This energy, actually potential energy, is the product of the force required to lift the mass of the robot against the acceleration of gravity, mg, and the height the robot must be lifted, h. The energy stability is the minimum value of mgh of each of the sides of the support polygon. It assumes that all mass is concentrated at the center-of-gravity. Figure 3-5 shows the energy stability of Ambler standing on a flat floor.

In this example, the energy stability has the greatest value where the distance to the nearest support polygon side is the farthest. This observation—that stability increases as the distance to the nearest support polygon side increases—is appropriate in level,

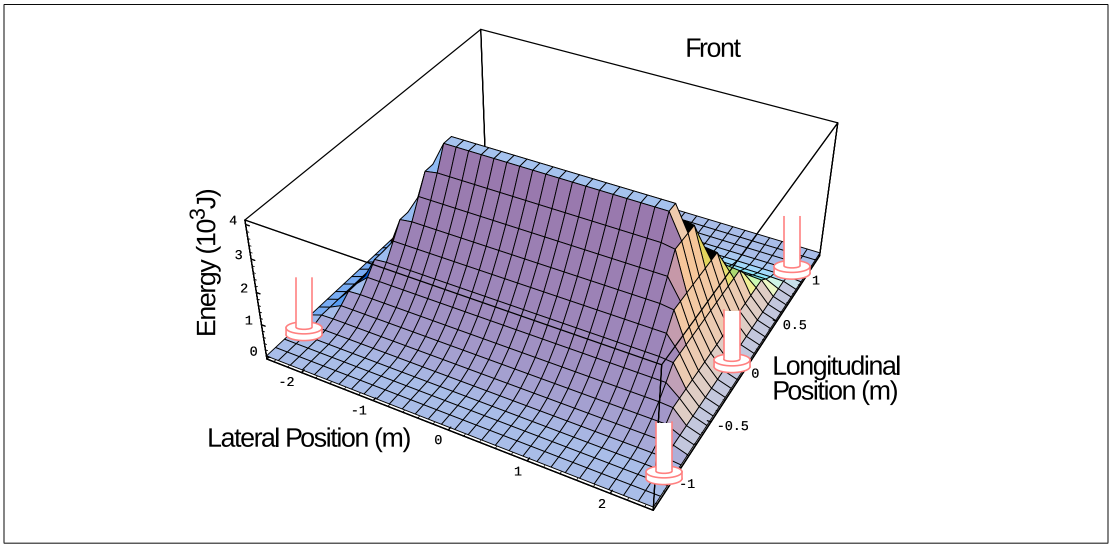

Figure 3-5: Ambler's energy stability while standing on level terrain (feet superimposed to illustrate the relationship to Ambler's stance). The center-of-gravity can be anywhere along the peak of the function for equal maximum stability, showing Ambler's ability to move laterally with maximal stability.

flat terrain but does not apply in rough terrains where leg extensions and the heights of foot positions vary.

Energy, *e*, is computed for each possible position of the center-of-gravity by equation [3-1], in which *r* is the radial distance to a foot and α is the angle formed with the gravity vector. When the feet are in arbitrary positions, a support polygon edge appears as in

$$\begin{aligned} e &= mgh \\ &= mg\|\vec{r}\|(1-\cos\alpha) \end{aligned} \tag{3-1}$$

Figure 3-6, in which β is the angle formed with the vector normal to the level plane.

In three dimensions the energy is computed by [3-2] which uses *r* the radial distance to the foot, β the inclination of the support polygon edge, and *z* the vertical extension of the leg. Messuri and Klein formulated energy stability with $h = \|\vec{r}\|(1-\cos\alpha)$ but since $z = \|\vec{r}\|\cos\alpha\cos\beta$ when z is available directly, a simplification is possible.

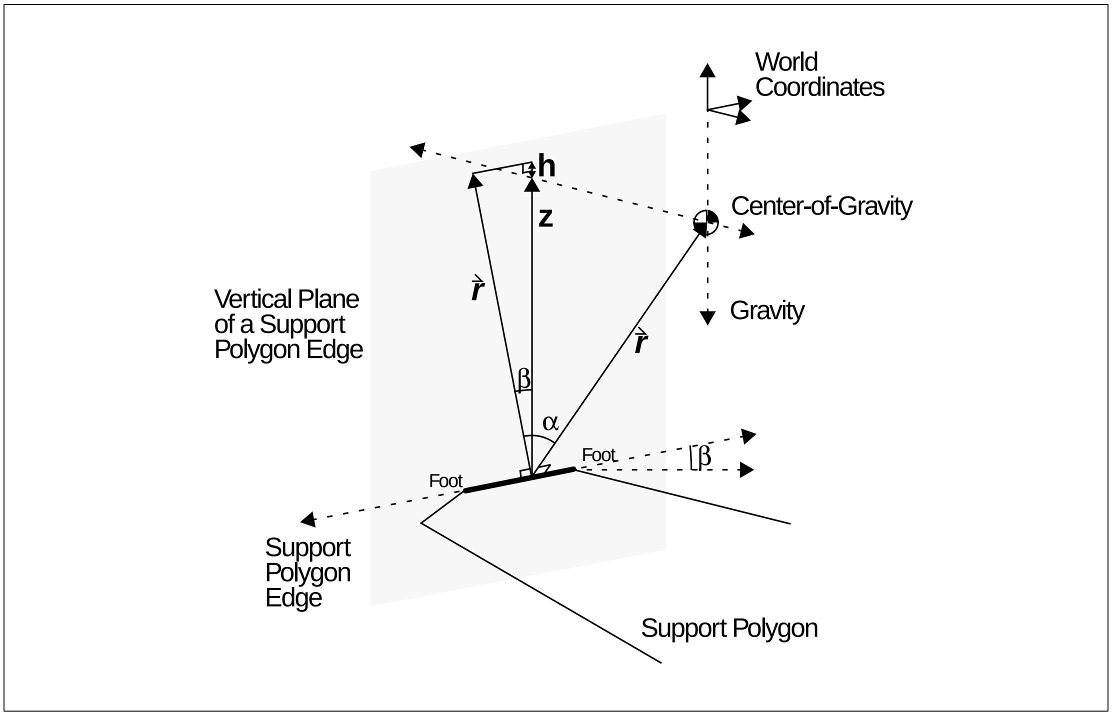

Figure 3-6: Motion of the center-of-gravity to overturn with feet in arbitrary positions (shown in 3-dimensions).

In [3-2], cg_x represents the x position of the center-of-gravity, f^n is foot n and i_x is the x position of the intersection of r and the line of the support polygon.

$$
\begin{aligned}
e &= mg(\|\vec{r}\|(1-\cos\alpha)\cos\beta) \\
&= mg(\|\vec{r}\|\cos\beta - \|\vec{r}\|\cos\alpha\cos\beta) \\
&= mg(\|\vec{r}\|\cos\beta - z)
\end{aligned}
\tag{3-2}
$$

where $$\|\vec{r}\| = \sqrt{(cg_x - i_x)^2 + (cg_y - i_y)^2 + (cg_z - i_z)^2}$$

$$\cos\beta = \sqrt{\frac{(f_x^n - f_x^{n+1})^2 + (f_y^n - f_y^{n+1})^2}{(f_x^n - f_x^{n+1})^2 + (f_y^n - f_y^{n+1})^2 + (f_z^n - f_z^{n+1})^2}}$$

Figure 3-7 shows Ambler’s energy stability in actual rough terrain where leg elevations differ by a meter.

The Amber gait planner uses the energy stability constraint to disallow those stances that are inherently unstable. Other stances that fail to meet a minimum stability criterion could also be eliminated, but this opens the question of assigning arbitrary thresholds and weights, and leads to the problem of combining dissimilar constraints.

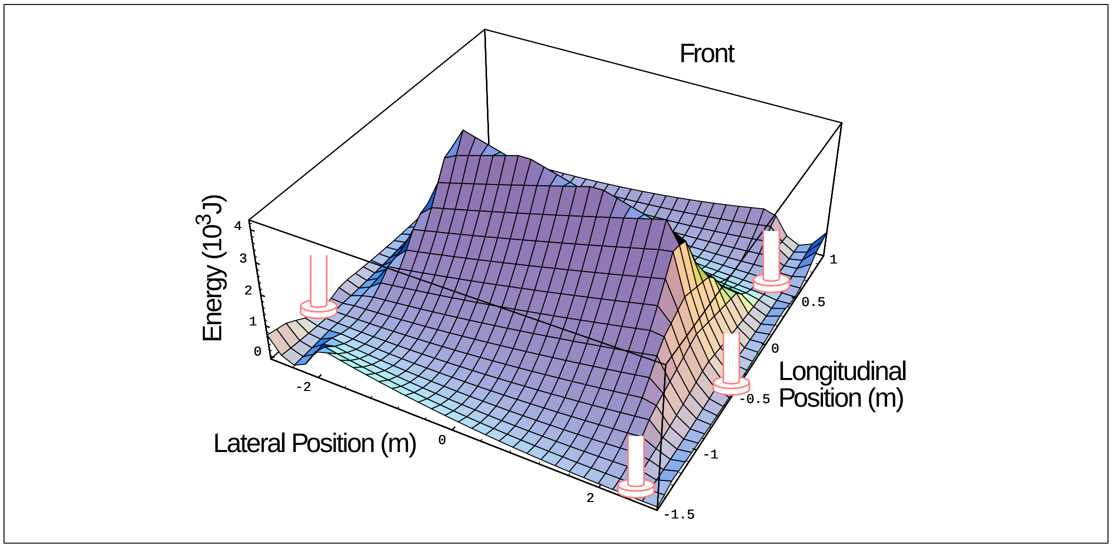

Figure 3-7: Ambler's energy stability in rough terrain. With the legs at different elevations and uneven spacing the ridge of maximal stability is skewed.

Problems combining constraints

Ambler uses a combination of analytic and search-based planning techniques to plan its gait. It uses analytic techniques to limit the possible motions by considering kinematics of the robot. The knowledge of the terrain is used to further limit possible motions. Stability considerations eliminate motions that are unstable. What remains are motions of acceptable stability and varying productivity, and evaluations. How to reconcile conflicting priorities—stability versus progress versus footing—to choose the best solution?

Many solutions have been posed to weighted combinations of dissimilar constraints. [Arkin89b] Min proposed a neural optimization network that combines a number of "energies," for example to increase stride, to maintain static stability, to avoid kinematic limits, or to avoid foothold forbidden areas. [Min92] The energies are combined as a weighted sum and differentiated with respect to time to obtain network equations. The neural network replaces a search algorithm to combine dissimilar considerations—its output is the desired foothold locations.

The Ambler gait planner provides an adequate solution to combining constraints but not a comprehensive one. The desired foothold is selected by eliminating all the footholds that do not meet minimum thresholds for each mobility and stability constraints and then selecting the foothold that results in the longest stride. This method of combining constraints adequately satisfies all constraints and provides productive advance.

Summary

- Gait planning, as an instance of motion planning, is inherently complex and a complete optimal solution is probably intractable. No solution has attempted to evolve the positions of all degrees-of-freedom over a period of time.
- A number of approximate, satisficing solutions have been posed. Simplifying assumptions include flat, unobstructed terrain and regular, periodic gaits. Analytic

methods have been successful under these assumptions. Rough terrain solutions have typically involved complete knowledge of the environment and restrictions on motions within a heuristic search for adequate motion.

- Reasoning approaches, because they involve extensive computations even in the most simplified cases, do not typically respond in real time. They run in controlled simulation or in advance of action, not direct by sensor input.
- To walk, Ambler also requires extensive and accurate information about its environment. Without a detailed kinematic model and map of the terrain, it cannot plan a gait. The gait that results is a prescription for crossing that particular terrain.
- Development of gait planning for Ambler revealed the importance of reasoning about constraints. Constraint-based planning produces satisfactory gaits and reduced complexity at the expense of optimality. Ambler's gait planner has been quite successful and can plan a free gait through rough terrain. Its gait plan is periodic and regular in benign terrain, becoming irregular only in the most rugged circumstances.
- Planning does offer the advantage of anticipating future events. Assumptions based on models and predictions may be flawed, but they can still provide valuable guidance for controlling gait. Estimates of how high the obstacles are and which stances are more stable, while not identifying a single gait to apply, restrict consideration to groups of useful actions.

Chapter 4

Performing patterns and plans

In **Performing patterns and plans** I first describe fixed gait patterns exhibited by animals and methods by which they can be modeled. Using a fixed pattern avoids the complexity issues involved in planning a gait deliberatively. I develop the position that alone, neither a fixed pattern nor a plan is enough to ensure reasonable performance in natural terrain. During execution the robot must respond to unpredictable events and adapt its actions.

This type of error detection can lead to replanning, as with another walking robot, Dante I, which reactively executes a gait plan, modifying it on-the-fly. I will describe Dante I and its method of reactive gait execution. Error recovery, a step beyond error detection, requires fast reaction. Dante I takes the first step to detect errors in its plan but cannot always recover—it is not particularly robust.

It is also appropriate to consider how productive various approaches are. I begin by compiling characteristic measures of various walking robots. There are few metrics of comparison and none that distinguish walking capability without regard for a specific robot. This makes it difficult to argue which is best or most productive. It is clear that few robots rival the capability of animals.

Fixed gaits and fixed patterns

The analysis of gait has ancient origins in observations by Aristotle. In more modern times, it is often associated with a bet about a trotting horse. Did the horse always have at least one foot on the ground, or were there periods of the gait when all the feet left the ground; was there a ballistic phase? Eadweard Muybridge, a photographer, was asked to settle the dispute and devised a way to capture a sequence of photographs of the trotting horse. In fact, the horse did take all its feet off the ground and Muybridge went on to photograph the regular periodic (or fixed) gaits of other animals, publishing his results in 1899, *Animals in Motion*. [Muybridge57]

Symmetric periodic gaits

The number of unique sequences of placing a leg on the ground is (k-1)! for a k-legged machine. But placing sequences alone do not define a gait; the number of possible leg lifting sequences must also be considered, so the number of nonsingular gaits (those in which no lifting or placing events are concurrent) events is 2n per cycle. McGhee, in [McGhee68a], derived this and identified the number of distinct gait-event permutations as N(k) = (2k-1)! for a k-legged machine or animal. For a horse N(4) = 5040, and for a beetle, N(6) = 39,916,800. The centipede *Scutigera* has 26 legs and 1.5×10^{66} possible gaits, although it employs only one!

Most of these permutations of stepping event sequences are not physically realizable as walking gaits. They involve too few supporting legs in the air or are sequences that offer no particular advantage over regular, symmetric patterns. For example, of a hexapod's 40 million or so gaits, only thirty are viable follow-the-leader gaits, five of which are symmetric. [Özgüner84]

Some gait symmetries are overt, for example when an animal bounds, moving both front legs together and then both back legs. Other symmetries are more subtle, for example the left legs may follow the sequence of the right legs but half a period out-of-phase. Still, the gait of a bilaterally symmetric animal can fail to be bilaterally symmetric (called symmetry-breaking) while still having symmetry by interchanging sides and shifting the phase.

Wilson, in [Wilson66], proposes that all six-legged gaits can be accounted for by some simple rules: (1) leg *protractions* proceed in metachronal sequence, from back to front, and no leg protracts until the one behind is in a supporting position; (2) *contralateral* legs alternate in phase; (3) protraction time is constant; (4) *retraction* time is inversely related to step frequency; (5) the interval between steps of adjacent legs is constant, but the interval between the foreleg and hindleg steps varies inversely with frequency.

These rules, which are sufficient to generate all the gaits depicted in Figure 4-1, essentially define gait as a function of the frequency of leg movements. With the protraction time constant, gait is generated by changing just the retraction time. This model smoothly transitions from the slow speed (wave) gait with a long retraction time to the high speed (tripod) gait with a short retraction time.

Certain aspects of these rules oversimplify behavior or aren't universally true of all species. Pearson observed that some stepping, particularly by the middle leg pairs, occurs in-phase, not in strict antiphase. [Pearson84] A weak dependence of protraction time on overall speed is also observable.

Asymmetric aperiodic gaits

Periodic gaits are stable and efficient on smooth terrains. For most of the terrain confronted by walking robots, periodic gaits are well-suited. Rough terrain may sometimes necessitate free gaits, in which any leg can move at any time to provide support and propulsion. A planner that reasons completely about the constraints on

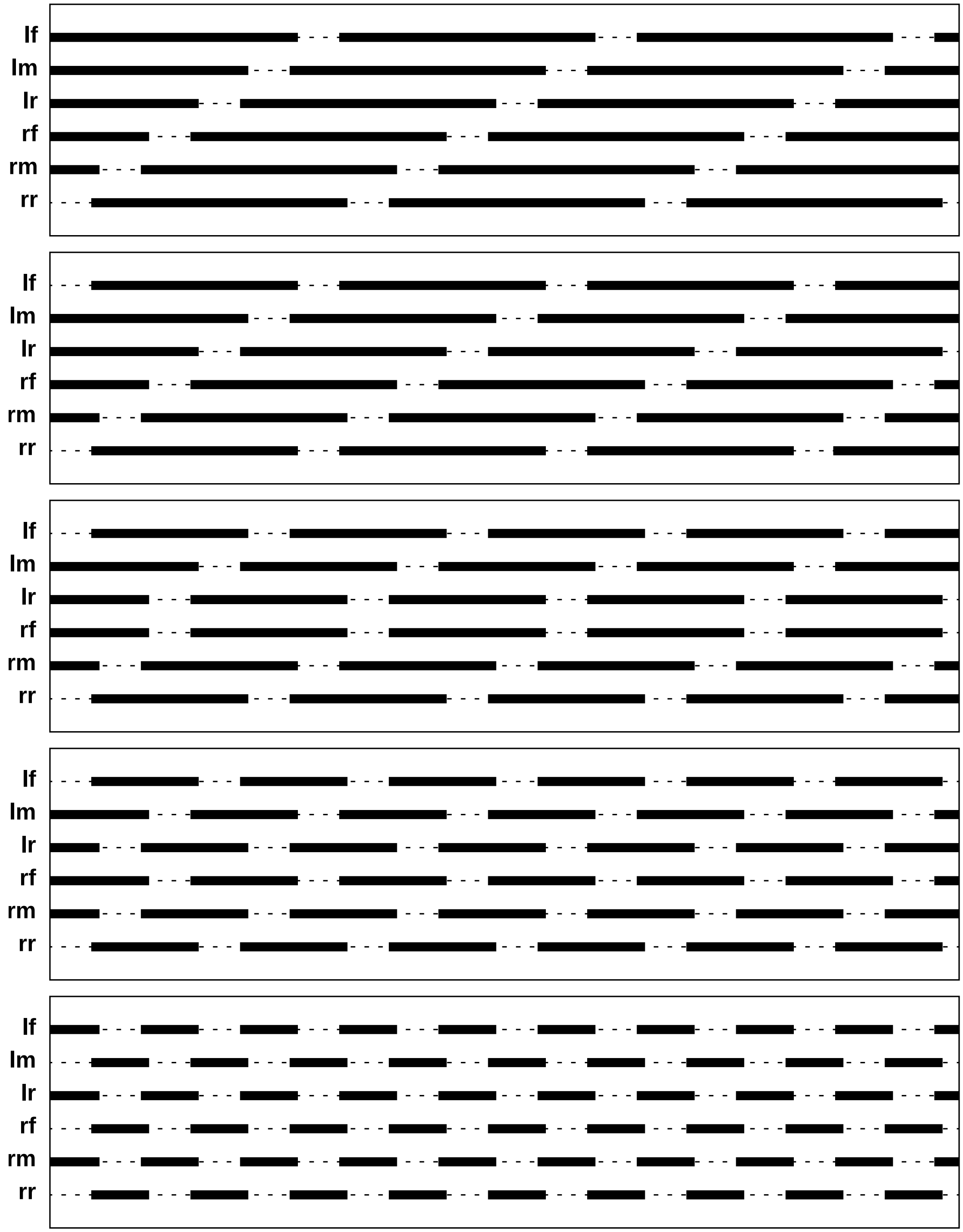

Figure 4-1: Basograms of hexapod (cockroach) gaits. Dark dark bars indicate when the leg is in contact with the ground supporting and propelling the body, dashed lines indicate the leg is out of contact, recovering forward. Note how the pattern shifts as only the support phase decreases.

vehicle motion is needed to create free gaits, because it requires situation-specific optimization of stability and maneuverability.

Describing and modeling regular gaits

Gait can be described in different formal ways, such as gait diagrams, support patterns, foot formulas, and finite state models. Each representation is a description of one aspect of a complex phenomenon.

Coupled nonlinear oscillators model rhythm

The symmetry of animal gaits has been compared to the oscillation in networks of symmetrically-coupled nonlinear oscillators (central pattern generators). Each type of network coupling generates a characteristic set of gaits. The transitions between gaits are modelled as symmetry-breaking bifurcations. [Collins92a]

Collins has shown that (for quadruped [Collins92b] and hexapod [Collins93] gaits) the oscillation patterns for several possible arrangements of symmetrically-coupled nonlinear oscillators correspond to the gaits commonly employed by insects. For quadrupeds, this change in gait can be modelled as four distinct, but symmetrically coupled, central pattern generators. Several different configurations of six coupled nonlinear oscillators are possible models of locomotor central pattern generators in hexapods. This provides a way of generating the fundamental rhythm of a gait.

Finite automata model sequencing

Finite state sequential logic may be useful in modeling gait if it is representable in the necessary form, namely that gaits involve finite states and that events are sequential. Is gait a finite state sequential process? Some components of a gait can be described in this framework, such as an individual leg stepping cycle, since it is sequential and can be associated with distinct states. Most such models include transitions in only one direction, unlike Figure 4-2 in which I have included two transitions for slips and

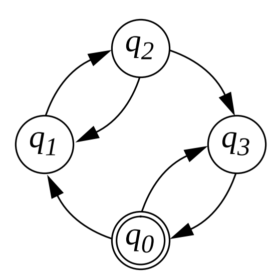

Figure 4-2: Transition diagram for finite automaton of single leg cycle. The nominal cycle and transitions that return legs to lowering and raising in the event of slips (lowering) and bumps (raising).

bumps. Finite automata are defined by a particular language of states and transitions. [Hopcroft79] In this example the states $\{q_0,q_1,q_2,q_3\}$ represent retracting, raising, protracting and lowering, respectively. The transition between q_n and q_{n+1} occurs as the leg changes from one state to the next, for example from retracting to raising. Transition from q_2 to q_1 is by a contact event and q_0 to q_3 is from a no-contact event. Many other languages are possible: Raibert used five states (thrust, unloading, flight, landing, and compression) [Raibert86]; Kwak used seven (support, lift, return, ready, advance, descent, contact, and support). [Kwak88]

Tomovic, in [Tomovic90], proposed a cyclic representation of locomotion, using a finite state automata, that emphasizes the coincidence of multiple leg states as well as phase shifts between the leg subautomata.The subautomata are supposed to synchronize so that ipsilateral pairs are a half cycle out of relative phase. This finite state machine can operate synchronously with each transition requiring equal, fixed time, or asynchronously, initiated and terminated by feedback signals derived from sensory information. Tomovic has suggested that comprehensive formal models have failed to reduce gait to a control theory because of inherent limitations in the modeling method.

McGhee has developed a different use of the finite state machine: to encode whether each leg is on the ground or in the air. [McGhee68a] The mechanism state is represented by a binary code and transitions encode viable changes in support. This provides a compact description of a periodic gait.

By considering multiple legs moving—not in a crawling gait, in which by definition only one leg changes state at a time—it is apparent that gait is a parallel process of infinite states.

Petri Nets model coordination

Gaits that incorporate spontaneous correction to disturbances are nondeterministic. Nondeterministic finite state machines exist (and are reducible to deterministic FSMs with many states) but do not easily allow modeling synchronization. Petri Nets model nondeterminism and synchronization quite naturally. They are a graphical and mathematical modeling tool with a unique pictorial syntax. Petri Nets are useful as a descriptive representation of concurrent, asynchronous, distributed, parallel, nondeterministic and/or stochastic systems. [Murata89] They are useful in describing behaviors because methods exist to prove their properties, including liveness and safeness.

A Petri Net is a specialized directed graph comprised of places (drawn as circles) and transitions (bars) connected by arcs either from a place to a transition or from a transition to a place. A transition (an event) has input places (preconditions) and output places (postconditions). A Petri Net always has a marking (a state) that assigns which places have tokens. Diagrammatically, tokens are black dots. At each transition firing, if a transition has tokens at all of its input places, then it can fire. If it does it removes a token from each input place and puts a token in each output place.

Figure 4-3 is a Petri net model of frame-walking with turning. It depicts two groups of legs that alternate stepping and supporting. The move and turn transitions happen in parallel but must synchronize to proceed to lower a frame.

Applying fixed gaits

Fixed, periodic gaits are those in which the legs follow a fixed repeating pattern of movement. Some walking robots have a fixed mechanically intrinsic gait with only one variable, the rate of advance. With the *step* height, *stride* length, and *phase* relationship fixed, the gait can be specified by just the rate. This is common in frame-walking robots, which walk by alternately recovering groups of legs, typically the legs on each of two

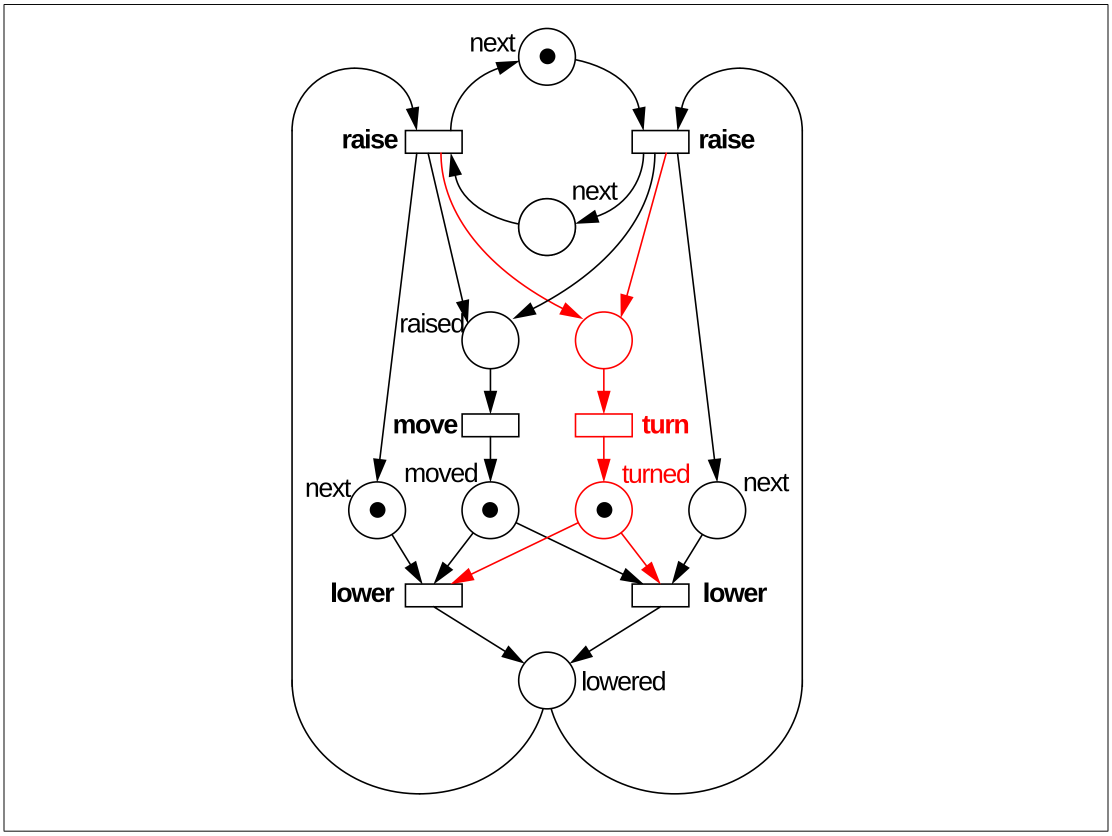

Figure 4-3: Petri Net representation of a frame walking cycle with turning. A turn transition occurs concurrent but not necessarily in synchronization with the move transition.

frames. Robots that have additional degrees-of-freedom can produce a sequence of movements with incremental motions. A periodic gait exhibited by these robots often follows a specific stepping pattern with parameters like step and stride adjusting to the situation and adapting to the terrain. [Whittaker93]

A fixed gait offers simplification because it is specified and optimized prior to actual walking. It can be optimized for speed or for stability. The result is predictable, reliable, and often very efficient in its intended domain. The Adaptive Suspension Vehicle, a hexapod walking robot, demonstrated impressive performance with a number of periodic gaits including a *tripod* gait and wave gait. [Waldron84] [Song88] Because leg movements are predetermined, minimal sensing (often only leg positions and forces) is required to apply the gait in favorable environments. [Lee88]

To surmount terrain obstacles and discontinuities, a gait can be tailored to each type of obstacle. For the ASV, gaits were developed to cross ditches and climb over obstacles. [Choi88] A rule-based selection mechanism chose the appropriate gait pattern. This approach is effective with specific obstacles, but is problematic because the catalog of special gaits grows large and selecting an appropriate gait becomes complex.

Gait is a shifting pattern

Using fixed gaits avoids the gait planning problem. Often, a walking robot can successfully apply periodic gaits and will be productive and robust. Indeed, optimal speed and stability performance is provided by regular, periodic gaits. In rough, irregular, or complex terrains, periodic gaits are insufficient because they cannot adequately adapt to the terrain irregularities.

There are two reasons why gait is sometimes a shifting pattern, not a fixed one: first, transitions between periodic gaits are necessarily aperiodic and second, natural terrain forces variation in the gait.

To transition between fixed, periodic gaits requires evolution of the gait cycle's frequency. Animals do this very smoothly as a result of some timing mechanisms [Grillner85] but even they do not linger in a gait that is irregular. Kumar showed that some shifts in periodic gaits can be made by varying leg retraction times (adjusting the periodicity), but this is not always stable. [Kumar89b]

Adapting a gait to rough natural terrain, specifically modifying step height and stride length, shifts the pattern of the gait. It does not seem reasonable to expect to walk through irregular terrain with a regular gait. The robot walking in natural terrain must adapt its gait; it cannot always apply a fixed pattern.

Planning alone is insufficient

There are a number of reasons to doubt that planning alone will succeed in guiding a walking robot in natural terrain.

Complexity, simplification, and finite available time

Planning is either intractably complex or unrealistically simplified. Gait planning is NP-hard, so optimally solving gait problems will always require complex algorithms and exponential time. For the most part, gait is a process to regulate, not a goal to achieve. A gait can be optimal but more typically it is satisfactory. This arbitrary nature makes it difficult to specify what to plan.

Non-optimal and heuristic solutions make assumptions about what can be simplified or ignored, and the relative importance of constraining factors.

Accurate sensing and precise execution

The world and the robot must be accurately modeled despite the fact that adequate sensors do not exist. Planned actions cannot be executed so precisely (or measured so accurately) that the robot cannot quickly deviate from the plan.

As Adachi has observed, most adaptive gait control schemes that have been proposed require that the surrounding environment be precisely defined; since it is difficult for the robot to obtain such perfect information, these schemes are all evaluated in simulation. [Adachi93]

Inherently unpredictable world

The world and the robot's interaction with the world are inherently unpredictable. Complete plans are infeasible, and lengthy precise plans are impractical.

All these difficulties aside, deliberative planning is sufficient in some domains—those in which the environment is measurable and predictable. In such a setting, deliberative reasoning can produce adequate results. The typical characteristics are that: the world will be stable and will behave as predicted; the time consumed in planning is independent of time that can be devoted to execution, so the efficiency of the planner has no effect on the feasibility of the plan; the information available to the planner is complete and execution will be flawless; and any initially correct plan will remain correct and can be carried out. [Agre90]

All these assumptions are widely held as untenable for a robot that must interact with the real world. Not surprisingly, it seems that walking in rough terrain is not measurable or predictable to a degree that admits a solution by deliberative planning.

One way to avoid planning is to always remain in the execution phase, responding reflexively. Gat described reactive actions from the stored internal state: reflexes involve minimal state if they are direct stimulus-response mappings. [Gat94] Such a system may reactively execute a plan, detect errors, and then recover.

Dante I, a rappelling octopod

Dante I is an octopod robot that demonstrates natural terrain walking by reactively executing a gait plan.

Volcano exploration

Manned entry into active volcanoes is exceptionally dangerous and typically yields sparse data. The purpose of the Dante Project is to develop walking robots to explore volcanic craters, so volcanologists can study them from safe, remote locations and fully observe ongoing activity.

Dante I’s mission was to sample the hot gases released inside the summit crater of Mount Erebus in Antarctica where air temperatures drop to -50°F but fumaroles reach 700°F, the wind can blow at 30 knots, and the crater slopes range between 50° and 80°.

Dante I walks and rappels with an alternating tetrapod gait

Dante I is an eight-legged robot that can rappel up and down steep slopes and surmount body-scale obstacles. In Figure 4-4, Dante I is shown on benign terrain with the legs of the outer frame raised. Its eight pantographic legs are arranged in two groups of four on an inner and an outer frame. Two drivetrains, one for each frame, drive the stepping motion of that frame’s four legs. Unique four-bar linkages on each leg mechanically convert a rotational motion into a stepping motion, shown in Figure 4-5. The mechanical coupling, resulting from driving all four legs of a frame together, reduces external force loops and enables an intrinsic gait with only one motion.

To walk, four legs simultaneously lift and reach forward while supporting legs propel the body. The body moves continuously—as one frame places, the other lifts off. Each of the legs can individually adjust its height, compounding the nominal stepping motion and enabling Dante I to avoid obstacles and adapt to terrain discontinuities. The frames can also rotate with respect to each other to change the heading.

Dante I’s tensioned tether provides a reactive force to gravity. The tether reel, mounted in the robot’s midsection, has an integral sensor to measure tension magnitude and direction. With these measurements and force measurements from the feet, the forces and moments being applied can be computed. Knowing these forces, the tether is servoed to counteract the gravitational force that would cause shearing at the feet.

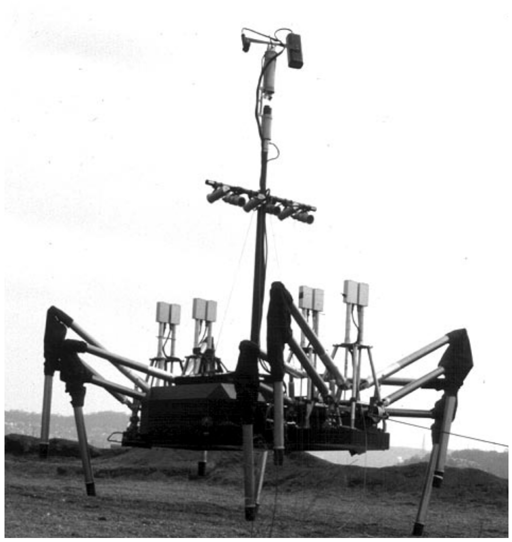

Figure 4-4: Dante I walking at the Pittsburgh slag heaps. The outer frame legs are raised. Each leg is a pantograph, knee joints are enclosed in debris covers. The eight lightly-shaded boxes each actuate the vertical motion of one leg. The mast carries two opposing trinocular stereo jigs and a conically-scanning laser rangefinder. The tether exits to the right.

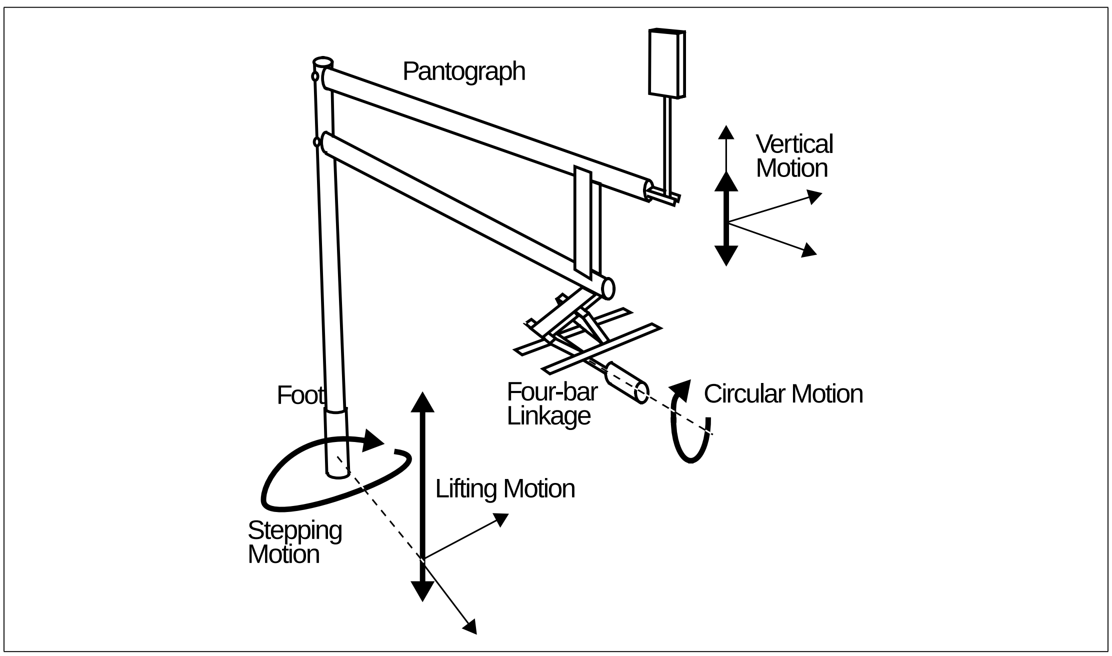

Figure 4-5: Dante I's pantographic leg coupled to a vertical actuator to lift the feet and to a four-bar linkage for an intrinsic stepping motion.

Stability with a tether

Constraints of static stability, such as the conservative support polygon, are not relevant since the mechanism is statically stable for all leg and body positions. With respect to dynamic stability measures, such as the energy stability constraint, Dante I is very stable on flat terrain. In Figure 4-6, Dante I is standing on a flat floor. It is well-suited to longitudinal motion; its energy stability function has a nominal ridge in the longitudinal direction, indicating that the robot is free to translate without jeopardizing

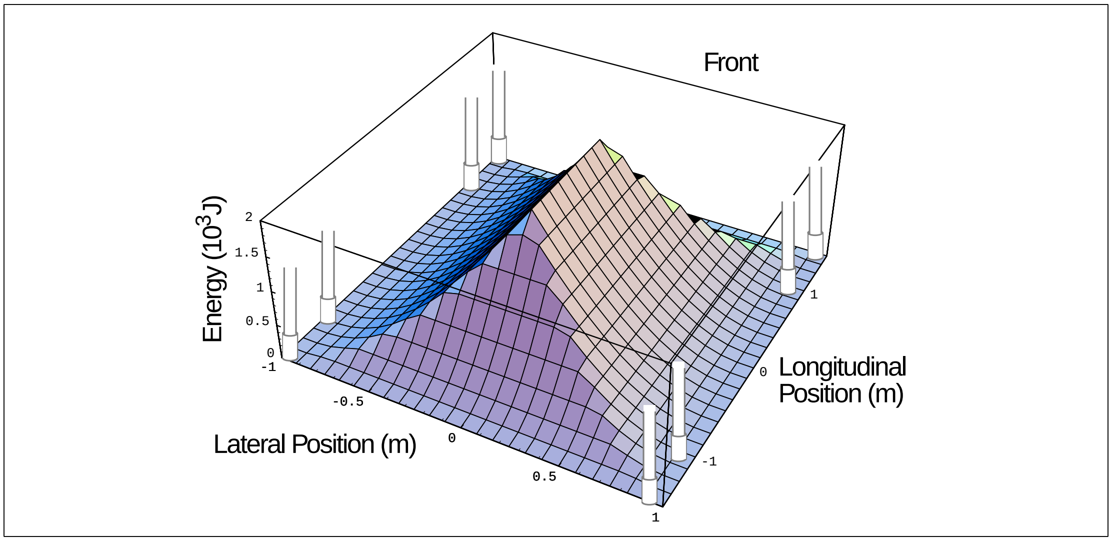

Figure 4-6: Dante I's energy stability. The ridge which indicates uniform stability is maintained during motion in the longitudinal direction.

stability. This ridge is longitudinal for Dante I in order to improve stability during a large stride, while for Ambler (Figure 3-5), this ridge was lateral, allowing greater flexibility in positioning the body during a stance. On sloped terrain, proper control of tether tension assures that Dante I's stability appears the same to the gait planner. In fact, with proper tether control, increasing slope is perceived as decreasing weight. The magnitude of the energy required to overturn decreases linearly until Dante I is on a vertical slope, the tip-over energy is zero and Dante I is hanging on its tether. [Nagy94]

Although its effect has been ignored to date, the tether actually impacts the energy stability by relieving some of the vertical component of the gravitational force. Dante I's proprioceptive sensors measure total weight (at the feet) decreasing as the slope increases, and as a result, the energy required for tip-over decreases. A more rigorous measure of stability must look at all the forces acting on the body when projecting the energy required for tip-over. [Nagy94]

Reactive gait execution by Dante I

Planning alone is insufficient for robust rough terrain walking. Not only must the gait adapt, but it must immediately respond to unpredictable events. Dante I responds to this unpredictability by executing planned motions relative to the current situation. It looks for inadequacies in its plan and initiates replanning.

Gait execution in Ambler's system is intrinsic to the planner. The planner decomposes its own plans, generates leg placements and body moves and feeds them to the motion controller system, which reduces them to servo reference values. If the motion controller signals any error (or when any of a collection of monitoring or exception handling routines detects an error), the plan is expunged and a complete replanning process is initiated. Because errors occur with some regularity, plans are seldom executed in their entirety. This is workable when planning consumes a relatively small portion of the overall sense-plan-act cycle, but as planning becomes more complex and expensive, plan failure and replanning are less acceptable.

Dante I performs independent reactive execution of its gait plan; it plans concurrently with and in advance of execution, selecting body and leg recovery heights for its frame-walking gait. It executes the gait, performing each motion relative to the current position, rather than to a predicted position, as Ambler did.

Dante I's gait generation software utilizes various constraints such as kinematics, terrain, and stability, to limit the range of possible moves. Unlike the Ambler, which can move any leg at any time, Dante I, with two fixed frames of legs, has a very limited set of possible moves. This greatly simplifies the planning problem, reducing it to optimization of stability and adaptation of leg height and body posture to the terrain.

Terrain is used to constrain the motions of the mechanism. As the body moves forward, lifting and lowering to maintain appropriate terrain stand-off, the leg extensions must adjust to avoid obstacles and to make contact with the ground at footfall. The gait planner interacts with the terrain mapper to learn about the terrain surrounding the mechanism.

Architecture for plan execution monitoring

The architecture of Dante I's software system reflects a sense-plan-act cycle that enables it to walk and to operate autonomously. (See Figure 4-7) Terrain is sensed by

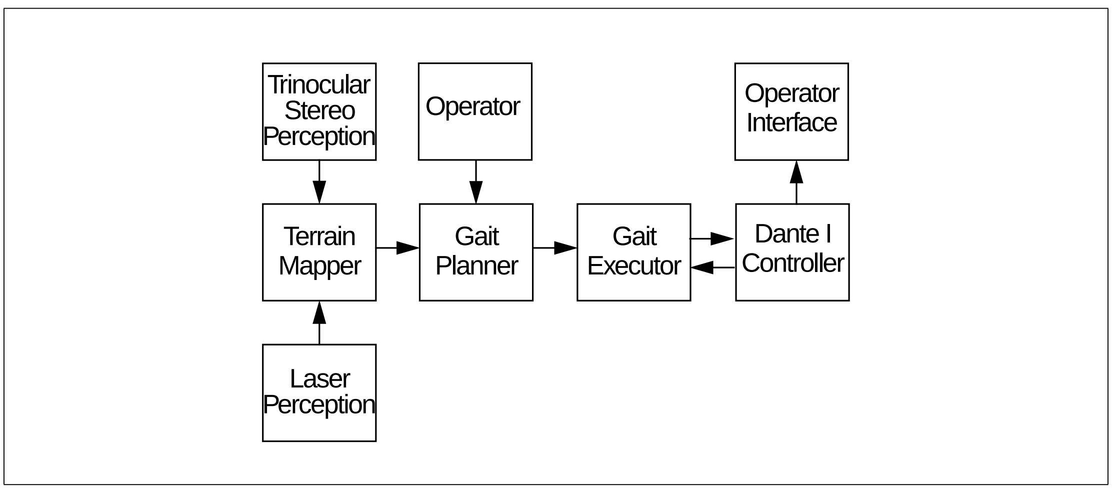

Figure 4-7: Dante I's software architecture showing information flow

both trinocular stereo and laser rangefinder perceptions. However, Dante I can be teleoperated without its perception sensors and can walk blindly by relying on human operators to direct its actions. Each perception module transforms raw sensor data into a depth map. The terrain mapper then transforms these depth maps into a common elevation map. Extensive map merging is not performed because the gait planner periodically requests maps in the current local coordinate system and there will likely be a single most recent map.

The operator gives instructions to walk, roll, pitch, yaw and lift/lower the robot. These instructions are in the form of desired trajectories Dante I is to follow. The gait planner takes these trajectories and breaks them down. First it plans all the body motions required to follow the trajectory. Then, if Dante I is operating autonomously, the body motion is adjusted to avoid collision with the terrain while still remaining as low as practical for stability. Next, the basic leg motions required to propel the body along the trajectory are generated. If Dante I is not walking blindly, the leg motions are adjusted to clear obstacles during the recovery phase and to ensure contact with the terrain during support phase. This planning process, termed gait generation, results in a plan to make Dante I walk along the commanded trajectory.

The gait plan is then passed to the gait executor. The executor monitors the current robot state and feeds the gait plan commands to the controller. The gait executor monitors progress looking for errors in the execution of the plan. This is a typical instance of plan execution monitoring. [Noreils95] When a substantial error occurs, the executor stops execution of the gait plan, determines the current robot state, and sends a message to the gait planner to initiate generation of a new plan beginning from the current location. Other than the plan itself, this requires almost no internal state.

The Dante I controller is a real-time process that runs on-board the robot. It coordinates the actuators and reads status from the encoders and other sensors. The operator interface display periodically polls the controller for status information about the robot. It displays a view of the robot with readouts of all the actuators and sensors. The user controls Dante I's actions by giving commands that go to the gait operator.

Planning simplifications

Like Ambler, gait planning for Dante I is primarily deliberative. The substantial development is that Dante I's gait plans are executed separately from their planning, allowing monitoring of their progress and correction of minor errors. There are two components in this approach to gait generation: a gait planner and a gait executor. It is significant that the gait planner does not decompose plans into primitive actions prior to their physical occurrence. Instead, it produces a series of stances (configurations) that the walker should assume. These stances are interpreted by the executor at run-time to derive actuator commands that transform the actual current stance (as opposed to the planned current stance) to the next planned stance. In the work completed thus far, monitoring performed by the gait executor results in error detection but not reactive error correction. It can detect when the actual current stance is not within tolerance of the planned current stance, but cannot produce corrective action.

Dante I's gait planner takes trajectories and plans a sequence of stances joined by the body and leg motions of the tetrapod gait. The body motions required to follow the trajectory are computed and then adjusted to avoid collision with the terrain, while still remaining as low to the ground as is practical for stability. An elevation map of the local terrain is used to satisfy terrain constraints. The leg motions that would propel the body along the trajectory are determined from kinematic constraints and then adjusted to clear obstacles during the recovery phase and to ensure contact with the terrain during the support phase. The stance sequence is then passed to the gait executor.

The gait executor transforms the stance sequences into specific actuator commands. It monitors the current robot state and feeds the commands derived from the stance sequence to the robot physical controller. The gait executor monitors progress, looking for errors in the execution of the plan. When a substantial error occurs, the executor stops execution of the gait plan, determines the current robot state, and instructs the gait planner to initiate generation of a new plan beginning from the current location. A future development is to embody the gait executor with enough capability to recover from these exceptional conditions.

Evaluating performance of walking robots

It seems appropriate to consider performance in a thesis about productive walking. How should performance be evaluated? There are a number of quantitative measures by which walking robots could be compared: speed, energy efficiency, physical capability, obstacle crossing, computing required. But there is no clear basis for comparison. Krotkov has discussed the lack of adequate metrics for comparing the performance of walking robots. [Krotkov92]

Speed may seem like an appropriate way to compare walking performance, but it is not. It is not because walking robots are vastly dissimilar. Two shapes are geometrically similar if they can be made identical by uniform changes in the scale of length; two motions are dynamically similar if they can be made identical by uniform changes in the scales of length, time, and force. [Alexander92] William Froude proposed a physical hypothesis that states that movements that are affected by gravity cannot be dynamically similar unless they possess equal ratios of kinetic to potential energy, [4-1].

$$\text{Froude number} = \frac{(\text{velocity})^2}{\text{length} \times \text{gravity}} \qquad [4\text{-}1]$$

This hypothesis has proven true in many systems.

Alexander has proposed that this hypothesis holds true of walking and showed that animals can be expected to walk in a similar fashion if their Froude numbers are equal. [Alexander84] Full, in [Full93], computed Froude numbers for walking robots to illustrate how far their capabilities are from animals. The best performing walking robots do approach some animals, like the turtle, but most are orders of magnitude away. In Full's original comparison several dynamically-stable walkers, including those of Raibert [Raibert86], were clearly correlated with animals (Raibert's quadruped trots at the same Froude number as a dog.)

In Table 4-1 robot gait, stride, stride frequency, speed, hip height, stride-to-hip ratio, mass, power, and Froude number are given for a number of walking robots sorted by Froude number. What does a comparison of Froude numbers show? It shows that walking robots aren't dynamically similar to animals; neither are they similar to each other. The gap between the performance of crawling gait robots like Ambler, Hannibal, and Turtle-1&2, are several orders of magnitude from a real turtle. Faster moving robots like TUM, ASV, and Mecant, are comparable to a turtle, although they do not employ a crawling gait. They instead use a tripod gait, like that of a cockroach, which is an order of magnitude beyond them.

Table 4-1: Comparison of robot characteristics, performance, and dynamic similarity

Robot	Gait	Stride m	Freq Hz	Speed m/s	Hip m	Mass kg	Power W	Froude v^2/hg
Ambler [Krotkov92]	Wave	3.4	0.002	0.007	1.0	2700	1900	0.000005
Dante I	Tetrapod	0.38	0.03	0.01	0.5	500	1000	0.00001
Dante II	Tetrapod	1.21	0.02	0.02	0.5	725	1500	0.00005
MELWALK [Kaneko85]	Tripod			0.01	0.2	35	80	0.00008
PV II [Hirose84]	Crawl			0.02	0.4	10	10	0.0001
ReCUS [Ishino83]	Tetrapod	2.5	0.03	0.07	2.2	27000		0.0002
Hannibal [Ferrell93]	Wave Ripple Tripod			0.008 0.02 0.04	0.2	2.7		0.00003 0.0002 0.0006
Turtle-1 [Adachi88]	Crawl Trot			0.03 0.05	0.23	17		0.0004 0.001
SSA [Donner87]	Tripod	0.75	0.06	0.05	0.2	900		0.001
Aquabot [Iwasaki88]	Tripod		0.08	0.03 0.13	1.0	700	1100	0.00008 0.002
Turtle-2 [Adachi93]	Crawl	0.15	0.3	0.05	0.4	20		0.006
Genghis [Brooks89]	Wave Tripod	0.1		0.04 0.12	0.15	2.5		0.001 0.009
Turtle	Crawl	0.2	0.6	0.1	0.07	—	—	0.02
TUM [Pfeiffer95]	Tripod			0.3	0.2	23	500	0.05
ASV [Pugh90]	Tripod	2.0	0.5	1.0	1.5	3200	26000	0.07
Mecant [Hartikainen92]	Tripod	0.7	0.7	0.5	0.5	1050	3500	0.1
Cockroach	Tripod	0.02	13.0	0.3	0.004	—	—	1.7

This shows that robots are not similar enough to use speed as a basis of comparison, even if ignoring differing environments, capabilities and objectives.

Summary

- Gait can be posed as a motion planning problem, but also as a pattern fitting problem. A number of gait patterns can be postulated mathematically, but only a small number are feasible. Of those exhibited by hexapods, the crawling wave is the most stable and the tripod is the fastest of the statically-stable gaits.
- Walking in natural terrain requires more than fixed gait patterns. If multiple patterns are employed, aperiodic gaits are required to transition stably; within a single pattern, adaptation and variation are necessary to accommodate the underlying terrain.
- Dante I executes planned motion sequences reactively. Its gait planner describes the gait in a sequence of stances that are interpreted at run-time. The gait follows a regular pattern, so the stance sequence varies only by the parameters detailing the amount of motion along the degrees-of-freedom.
- When traversing flat, clear terrain, periodic gaits are most efficient, hence producing a gait should degenerate to a periodic gait when possible. As the terrain varies, the gait must adapt and become aperiodic; Dante I does just this.
- Most walking robots are not dynamically similar to each other. This makes robot performance difficult to compare analytically. Different robots also address different applications, so some are energy efficient, others are fast, others are stable.

Chapter 5

Walking with reflexes and behaviors

In **Walking with reflexes and behaviors** I explore reactive and behavior-based approaches to controlling a mobile robot. Symbolic planning and reasoning can predict which gaits are feasible, but executing a precise action sequence is practically impossible. Behavior-based approaches offer a method of maintaining the character of the gait without requiring a precise description of how to walk.

I move from a discussion of methods, for which the contemporary literature is vast and growing, into issues specific to robot walking. I provide the principal design elements for a behavior-based gait controller that enables robust terrain adaptive walking, while still allowing stable servo control of motions and supervisory teleoperation.

I then introduce Dante II, a frame-walking robot, and describe the implementation of its behavior-based control system and provide representative examples of Dante II's performance, including excerpts of its descent into the crater of Mount Spurr.

Action controlled with reactions and behaviors

Part of the difficulty of executing a planned gait is that the world state cannot be adequately predicted a priori. But some things can be predicted, for example the approximate height of nearby objects or the property that a leg must leave the ground before it can swing forward, but most things cannot be predicted because they are difficult to measure quickly and accurately and are subject to change without notice. Walking requires a method of producing a gait with a minimum of prediction.

An architecture is a style, a principled organization of construction. Robot control architectures have been placed along a continuum from purely reactive to purely deliberative. [Mataric92] It is worthwhile to characterize reactive and behavior-based approaches as they apply here.

Reactive approaches implement a control strategy as a collection of mappings from sensed conditions to actions. Behavior-based approaches, which sometimes contain a reactive component, add internal representations and transformations of sensed and stored states in order to decide what action to take.

Reactive approaches minimize internal state and prediction

Purely reactive control implements a strategy of applying condition-action pairs to immediately available sensed or state information. [Agre90] These systems produce no internal models, perform no search, and rely on feedback from the world to modulate their direct coupling of sensors to actions. A reactive architecture is one that selects, adapts, or generates action sequences through its interaction with the world. Such a system can react immediately as the world changes.

Perhaps the core idea of a reactive approach is the appropriateness of its timescales. Reactive architectures, by simplifying their computation and not relying on predictions, are able to respond to events at the pace of the environment. That means that if it takes one second from when an event begins occurring until when an agent can no longer affect the outcome of the event, then regardless of anything else the agent may be capable of doing or doing concurrently, it has to respond in less than one second. It has to react.

In one example of a reactive system, Arkin developed motor schemas that specify an appropriate action for each place the robot may find itself. [Arkin87] To control a robot exploring unknown terrain, Miller showed that a few direct mappings of sensation to action could produce competent search and retrieval operations. [Miller92]

A reactive approach responds directly to the world as it is rather than as it is predicted. Some reactive architectures virtually eliminate internal state, but most keep it to a well-reasoned minimum.

Behaviors are useful organizing principles

Behavior-based systems may have reflexive responses and may incorporate a reactive component, but their computation is not limited to simple lookup. They may employ some, usually minimal, internal representation and may perform computations to determine what action to take.[Mataric92]

The use of behavior-based control was proposed for the control of autonomous robots by Brooks. [Brooks86][Gat93] Brooks has criticized the emphasis of narrow and rigid expertise over fundamental survival skills. [Brooks91b] Instead he advocates building robots capable of simple, robust and adaptive behaviors in unconstrained, dynamic, even openly hostile environments. To control these robots, Brooks makes used of a layered control system called the subsumption architecture. [Brooks86] It is based on finite state machines augmented by internal registers and timers. Each layer is organized around a particular task, such as object avoidance or edge following.

The behavioral approach characteristically rejects symbols and reasoning about gaits, instead embodying the gait generation in a control network. Such a network is patterned after a particular animal neural system or after an abstraction of a behavioral network. These concept-free (or representation-free) approaches have proven very effective in situationally-determined activities such as basic walking. [Kirsh91] While behavioral approaches can be formulated as a system of rules, they differ from the previously described rule-based planners in that they lack representation and any hierarchy of information abstraction for the rules to operate upon. Rules in this context map input, usually sensory, directly into output actions.

In a behavior-based approach, Brooks developed the Subsumption Architecture in which asynchronous modules, each an augmented state machine, communicate over low-bandwidth channels and assemble in layers. [Brooks86] Sensors are tied directly to reflex action. Higher layers can subsume the behavior of lower reflexive layers by suppressing their output, though lower layers continue to function as additional layers increase the behavioral complexity.

Brooks implemented walking in the Subsumption Architecture. [Brooks89] The network forms an abstraction of the behaviors necessary for walking. The robot Genghis performs a rear-propagated, ratchet gait. Within the behavior-based architecture, Genghis learned a tripod gait by reinforcing an incentive to keep legs from contacting each other. [Maes90a] Ferrell has continued the work started on Genghis with another walking robot, Hannibal. [Ferrell93] She has used a layering of 1500 behaviors to produce three periodic gaits, with the gait controller reactively responding to foot-scale obstacles in natural terrain.

An action selection theory that allows arbitration among goals while still producing fast and robust interaction with the environment may enhance the behavioral approach. [Maes90b] Behavioral agents would be able to trade off planning for adaptivity or thoughtfulness for speed, for example. This is important because the ability to direct the behavioral system is desirable. To “drive” a walking robot, it must be able to respond to some strategic directives.

In essence each behavior is a sometimes direct and sometimes complex mapping between some conditions and an appropriate action. There are many ways in which this mapping can occur—as simple as a logic circuit, or as a neural network, or as a rule-based production system.

Combinatorial logic encode reactive behaviors

Circuit diagrams are one method of modeling reactive behaviors. Reflexes such as “maintain a foot in contact” can be described in combinatorial logic. Figure 5-1 diagrams a simple circuit to maintain foot contact during the support phase and to keep the foot free during the recovery phase.

The lower and raise leg group signals are mutually exclusive. If the lower leg group line goes high, then the contact foot line and lower leg line also go high. When the contact foot line is set, it stays high and sends the free foot line low (because raise leg group will also be low). If the raise leg group line goes high, then the free foot line and raise leg line also go high. When either the vertical contact or horizontal contact sensor detects contact above a threshold, it goes high. If the vertical contact line is low (no contact) and contact foot is high, then the lower leg line goes high. If the vertical or horizontal contact line is high (contact) and free foot is high, then the raise leg line goes high.

Combinatorial logic is a precise language for describing reflexes. The circuit diagram tells exactly what should result from all the valid inputs. Some reflexes may be

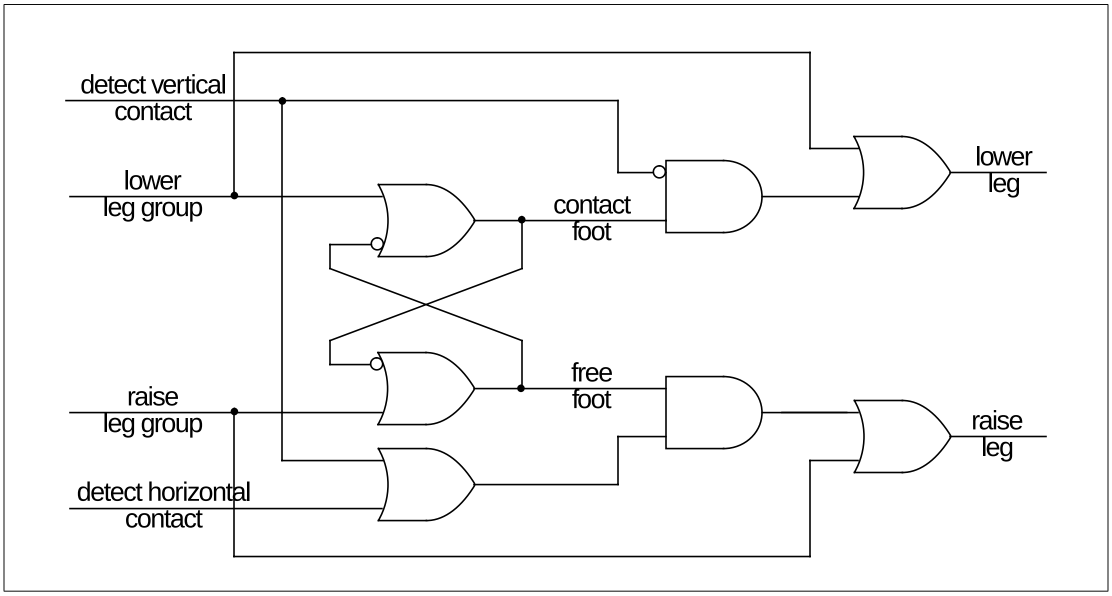

Figure 5-1: Circuit diagram for leg control that coordinates the raising and lowering of a leg with the motion of a group while simultaneously reaching to contacts.

amenable to direct implementation in combinatorial logic. Implementation in digital circuit hardware would likely provide the fastest reflexes available to a walking robot. Also, software mechanisms that construct “circuitry” necessary for repeated application of the logic may be viable. The Gapps/Rex languages [Kaelbling90] and teleo-reactive programs [Nilsson94] are examples. These systems offer the advantage that the circuitry (particularly that dealing with time-varying objectives) can be changed during execution.

Control laws adapt behavior to changing input

Control theory is applied to a number of aspects of walking and always provides fast reaction to some event. Sutherland’s walking machine used a control law to synchronize a series of hydraulic valves in order to produce a *ratchet* gait. [Sutherland83] An onboard human operator steered by affecting the control law to adjust the speed at which each side of the machine stepped.

Control theory has been applied to walking in order to maintain balance and adapt to irregular terrain. Regulating balance or equilibrium can be required to regulate dynamic or quasi-dynamic gaits, to distribute forces among legs, or to reject disturbances of the robot’s center-of-gravity. Dynamically-stable robots use feedback control laws to produce gaits that can reactively adapt to maintain balance. For statically-stable robots this regulation can occur at lower frequency to distribute forces and reject disturbances, rather than maintain balance.

Raibert controlled one- and two-legged dynamically stable mechanisms with three servo loops that produce independent actions. One loop controls vertical motion (hopping height), one controls body attitude, and one controls balance (foot placement)—which dictates the forward speed. [Raibert83b] More complicated control laws have been applied to a quadruped and have executed the more highly synchronized gaits of a horse.

To demonstrate rough terrain locomotion, Hodgins explored controlling the step length of an actively balanced biped. By adjusting running speed, running height, or duration of ground contact, three methods of controlling the step length were developed. Adjusting forward speed was most effective and allowed the biped to step on specific target footholds, leap over obstacles, and climb stairs. [Hodgins91]

A control based approach to locomotion in pipes was implemented in a hierarchical control architecture with reflexive behaviors in the lower layers. [Neubauer93] Each leg is controlled independently to maintain a force against the sides of the pipe or to avoid collisions in recovery. A central controller instructs the leg when to support and when to recover. This decentralized control still produces complex terrain negotiation.

Controlling walking with behaviors

I will describe the principles I have adopted in the design of a behavior-based controller for producing a walking gait.

Gaits in flat, obstacle-free terrain are regular and periodic, because there is nothing to prohibit this efficiency. Natural terrain is not usually uniform; it is by definition irregular. Applying a regular gait to irregular terrain is a difficult fit—since the terrain is aperiodic the gait should be as well. Rather than tie leg stepping to a clock, a temporal frequency, tie it to the terrain, adjusting the time to conform to spatial demands.

Developing walking first and then adapting to natural terrain seems backward. Several researchers have followed this direction, taking regular gaits and making them work in irregular terrain. [McGhee79][Ferrell93] But if the ultimate objective is rough natural terrain, then the robot must first be able to stand and adjust its legs and posture to conform to the terrain. The center of gravity must be free to move so that the legs can recover safely. Then the robot must step, detecting and reaching to contacts, with individual legs moving as the robot crawls through the terrain. Finally these steps can be organized into more complex gaits. This agrees with decomposition found by Celaya when trying to adapt an existing gait controller to rough terrain. [Celaya95]

To *stand* seems innate in a statically-stable robot. But the world is dynamic, and the robot has to keep its feet on the ground. When a foot is not in contact, it should move downward until contact is detected. This contact-seeking property applies when a foot slips, when the terrain crumbles, and after a step to begin the support phase.

To *posture* requires coordinated motions of the supporting (or all) legs. The relative extensions of the legs must simultaneously adjust to effect a new pitch, roll, or clearance from the terrain. Posture can be independent of other operations, and should be continuously functioning.

To *propel*, supporting legs must either discretely or continuously drive the body forward and thereby shift support so that legs approaching their kinematic limit can recover.

To *step*, a leg must stop contact-seeking and begin contact-avoiding. Remaining free of the terrain involves eliminating vertical forces by raising the leg, and then monitoring for bumps.

To *walk*, legs must be freed, recovered to a new position while translating and turning the body, and then placed back on the ground to support while other legs step.

While constituent attributes of walking may be described as standing, posturing, propelling and stepping, this does not constitute a hierarchical decomposition of the task. The behaviors which construct the system are not organized to first achieve standing, then posturing and so on. They form a nonhierarchical network. Indeed, the same mechanism which keeps the feet on the ground while standing also lowers the leg as part of stepping.

An important distinction to make is between anticipated and unanticipated events. Both are events that are expected at some time, but those that are anticipated are predicted at an identifiable time; those that are unanticipated cannot be forecast. Anticipated events occur with regularity and require a convergence of necessary resources, for example, step cycle, changing terrain pitch, changing terrain clearance, and obstacles. Unanticipated events are expected but unpredictable, like bumps, slips, and tips, and demand reactive response.

Behaviors share a prototypical task structure

The basic abilities that keep a walking robot safe and stable, and establish its gait cycle, are its ability to stand, posture, step, and walk. Asynchronous task-achieving processes, behaviors, embody these abilities. They act independently to achieve or maintain desired states, and interact to walk. Many concurrent processes perform communication, sensor data collection, motion servo control functions as well as behavior. Each behavior is designed as an independent process or task which can be executed in a multi-tasking operating system. And all of these behavior processes share a common structure, [5-1].

[5-1]

```
void behaviorProcess(behavior)
{
   while(OK){
      pendOnMessageQueueForExOrIn(&hibit);
      if determineExOrIn(hibit) {
         executeExhibitFunctionOf(behavior);
      } else {
         executeInhibitFunctionOf(behavior);
      }
   }
}
```

Some functions terminate and return to pend. Others peek for messages and return to pend if a message has arrived. Interrupts are a better implementation.

Behaviors produce action by modulating servo control

Some walking mechanisms are small enough that impact dynamics do not adversely affect them—these mechanisms need not be carefully servo-controlled or stable and can still perform many simple tasks. However, to grow these devices and perform more complex and forceful tasks an appropriate strategy seems to be to avoid violent collisions and destabilization, and to servo control each joint.

The objective is to control and coordinate the many degrees-of-freedom of a walking robot. A reasonable way to begin is to establish stable servo control over each motion.

The problem then becomes: what reference value to provide to each servo loop. One way to approach this is to recognize that, in effect, achieving a task is a matter of properly setting servo references. The Ambler and Dante I set servo references by having a planner determine them but it is also possible to have independent task-achieving behaviors set the references. Mataric has observed that behaviors can be thought of as smart servo loops. [Mataric92]

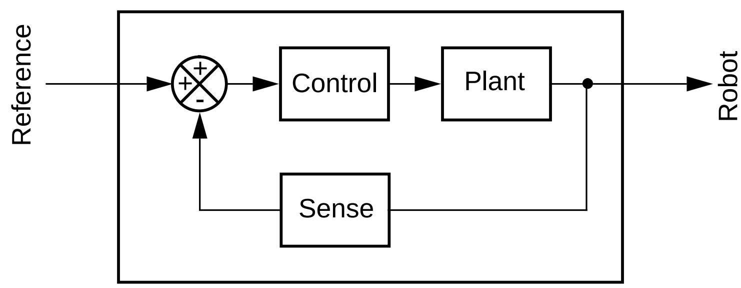

Figure 5-2: A feedback control system. It employs a control law (Control) to provide input to an actuator (Act) that produces, in this case, action by a robot. That action is sensed (Sense) and the difference between the sensed action and the desired action is used by the control law to further guide the actuator and eventually drive the difference to zero. This is called servoing and the sense-control-act cycle is the servo loop.

In feedback control systems, a servo loop employs a control law that provides input to an actuator that produces some action, as in Figure 5-2. The action is sensed and the difference between the sensed action and the desired reference action is used by the control law to further guide the actuator and eventually drive the difference to zero. Control theory is essential to robotics, to the extent that robots move and need a way to make that happen. For example, consider the `contact foot` behavior, depicted in Figure 5-3. It causes the foot to achieve and maintain contact with the ground.The

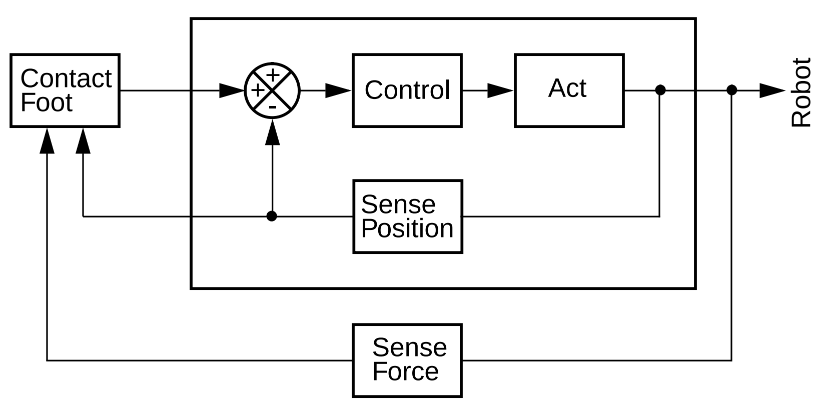

Figure 5-3: The `contact foot` behavior, a single concurrent process duplicated once for each leg, senses position and force information and produces a servo reference to maintain foot contact with the ground.

`contact foot` behavior observes the position and force state of an individual leg and produces a servo reference. When a supporting foot is not in ground contact, it should move downward until contact is restored. The `contact foot` behavior initiates each support phase and applies when a foot slips or the terrain crumbles.

Parameterization of the behavior process

To eventually allow for external guidance of the behavior-based controller, each of the behaviors is parameterized. This allows external modification and direction. These

Table 5-1: Parameterization of behavior tasks

Parameter	Position	Velocity	Acceleration	Force	Duration	Threshold
Frame translation	✘	✘	✘			✘
Frame rotation	✘	✘	✘			✘
Body height	✘	✘	✘			✘
Body roll	✘	✘	✘			✘
Body pitch	✘	✘	✘			✘
Pause					✘	
Leg height	✘	✘	✘			✘
Leg force				✘		✘
Leg strain				✘		✘

parameters can be adjusted during execution to continually modulate the character of the gait. This parameterization forms the basis of supervisory teleoperation and eventually, autonomous guidance. It is a novel development for behavior-based walking robots.

By appropriately selecting values for these parameters, the overall behavior of the walking robot can be guided. For example, the nominal height that legs raise can be tailored to the type of terrain the robot is encountering.

Behaviors interact in a heterogeneous activation network

There are two ways in which a behavior can produce action. The first, as described, is to modulate the input to a servo loop. The second is to effect the state of other behaviors. To do this, the behavior processes interact in an activation network—a heterogeneous network in which links are established to enable specific interactions to take place. The behaviors are networked by binary links that carry inhibit and exhibit control signals, but there is no hierarchy or layering. Each can potentially send a message to any other.

Several researchers have observed that asynchronous, heterogeneous networks may be appropriate to producing aperiodic gaits. [Donner84][Cruse93][Cherian93] This is also how animal nervous systems are organized and is believed to be the structure in which gait is produced.

Behaviors are either exhibited or inhibited

Each behavior process can be exhibited or inhibited as a result of inhibit and exhibit messages that are exchanged within the activation network. The inhibition/exhibition logic is simple: exhibit when receiving one or more exhibit signals and no inhibit signals. When exhibited it displays its behavior by obtaining sensor values and adjusting actuator position as a function of those sensor values. Exhibiting behaviors also send exhibit messages and/or inhibit messages to other behaviors. When a behavior process is inhibited it is unable to affect actuator position or other behaviors.

[5-2]

```
BOOLEAN determineExOrIn(hibit)
{
   /* Increment the number of exhibit and inhibit messages */
   exhibits += ((hibit&BIT_ONE)?((hibit&BIT_ZERO)?1:-1):0);
   inhibits += ((hibit&BIT_ONE)?0:((hibit&BIT_ZERO)?1:-1));

   /* Determine exhibit/inhibit state of the behavior */
   return((exhibits > 0) && (inhibits == 0));
}
```

When the process exhibits its behavior, it watches for signalled events and sensed conditions, and produces signals and actions.

Asynchronous two-bit messages for communication

The behavior processes do not communicate information to one another. They send only two-bit messages that influence the exhibition/inhibition condition of the recipient. The messages are send asynchronously and not tied to a synchronous clock-based signal that is continuously held high or low as is common in some behavior-based architectures. Messages indicate the rising or falling edge of an inhibit or exhibit signal. This might be implemented as two incoming message channels, one for inhibition and one for exhibition, which each receive one-bit signals: one for rising edge and zero for falling edge. But to allow real-time processes to pend on a single incoming message channel, each message is two bits: the first bit identifies inhibition or exhibition, and the second bit indicates whether the condition is beginning or ending.

Arbitration among conflicting behaviors

The arbitration among competing behaviors occurs explicitly; when one is exhibited it directly inhibits those with which it competes for resources.

Individual behaviors explicitly inhibit others that would come into direct conflict or would share a resource (like muscle isometric inhibition). For behaviors that share a particular resource, their servo reference values are additive.

Dante II, a rappelling, frame-walking robot

Dante II is a walking robot that has explored volcanic craters, at times walking autonomously—controlled by behaviors that produce tactile and postural reflexes and coordinated gait patterns.

Volcano exploration, revisited

Dante II, shown in Figure 5-4, is the second robot developed by the Dante Project. Its destination was Mount Spurr. The volcano erupted three times in 1992, spreading 200 million cubic meters of ash over Alaska. It is of interest because of its proximity to Anchorage and its potential for further eruptions.

Like Dante I, Dante II is a framewalker, although its configuration is substantially different. It has similar sensing modalities but greater on-board capabilities and a more mature off-board teleoperation interface. In July 1994, it entered the active crater of Mount Spurr, Alaska, measured gasses and temperatures, and observed fumaroles on the crater floor.

Figure 5-4: Dante II descending into the crater of Mount Spurr in Alaska.

Rappelling, frame-walking mechanism

Dante II's eight pantographic legs are arranged in two groups of four, on inner and outer frames. Each leg can individually adjust its position vertically to avoid obstacles and adapt to rough terrain. Body translation (along the Y-axis) is actuated by a single drivetrain that moves the frames with respect to each other, depicted in Figure 5-5. The frames can turn about the Z-axis to change heading. The maximum turn is 7.5°, so it is best to avoid obstacles in advance and minimize repeated turns.

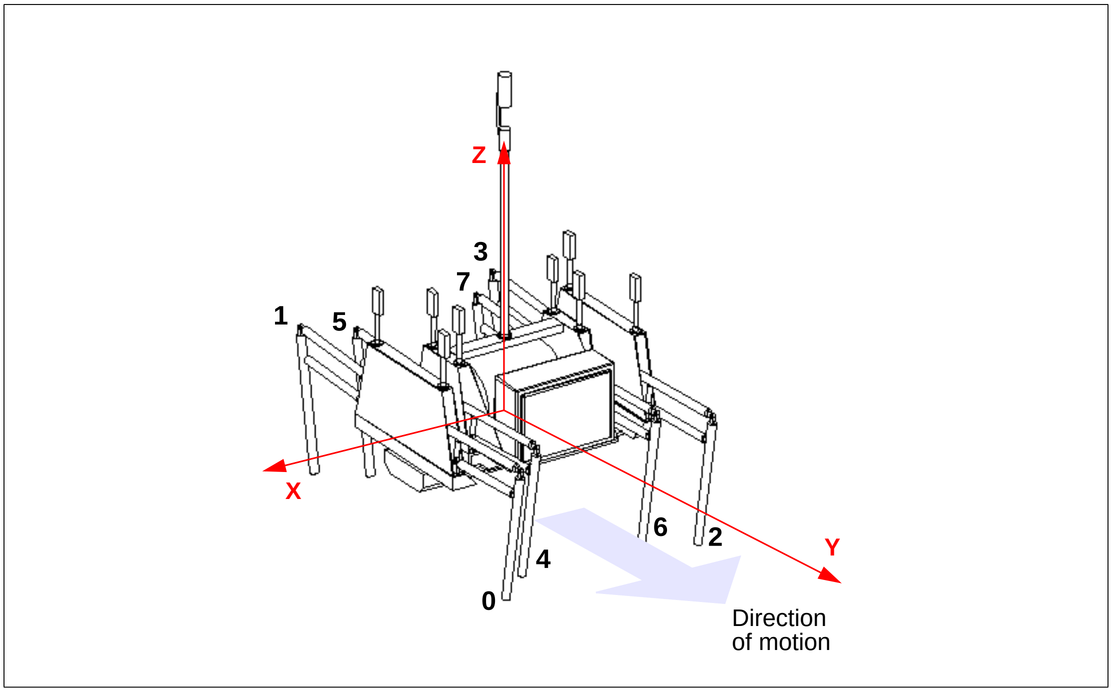

Figure 5-5: Dante II coordinates and leg numbering scheme. The leg number is determined by assigning a binary code of three bits meaning <frame><side><end> to each leg, thus leg 2 (010) is outer frame, left side, front end and leg 5(101) inner frame, right side, back end.

Dante II is statically-stable—it has no dynamic (balancing) phase in its gait cycle. But dynamic events certainly occur; bumps and slips could destabilize it. To rappel steep slopes, a tensioned tether mounted on the inner frame provides the reactive force to gravity. To walk, the legs on one frame raise up, while legs on the other frame support. The free legs recover to new locations as the frame translates, propelling against the supporting legs. When the inner frame is in motion, the tether spools in relation to tension and inclination to counteract the downslope component of gravity and to minimize shearing forces at the feet.

Sensing terrain topography

Dante II senses the terrain with both perceptive imaging devices, and proprioceptive position and force sensors, annotated in Figure 5-5. Atop the mast, a conically-scanning laser rangefinder measures the distance to the terrain in a 360° field-of-view. This depth map can be transformed into an elevation map of the surrounding area, used to identify feasible paths.

Each leg has a load cell mounted between the vertical actuator and the pantograph mechanism to measure vertical foot force, and a pair of strain gauges adhered to its vertical member to measure lateral loads. The strain gauges detect continuous high loads or transient bumps of small magnitude (less than a pound). Potentiometers encode joint positions and inclinometers measure gravity-relative posture. These sensors characterize the posture of the body and the positions of and forces on the eleven actuated motions.

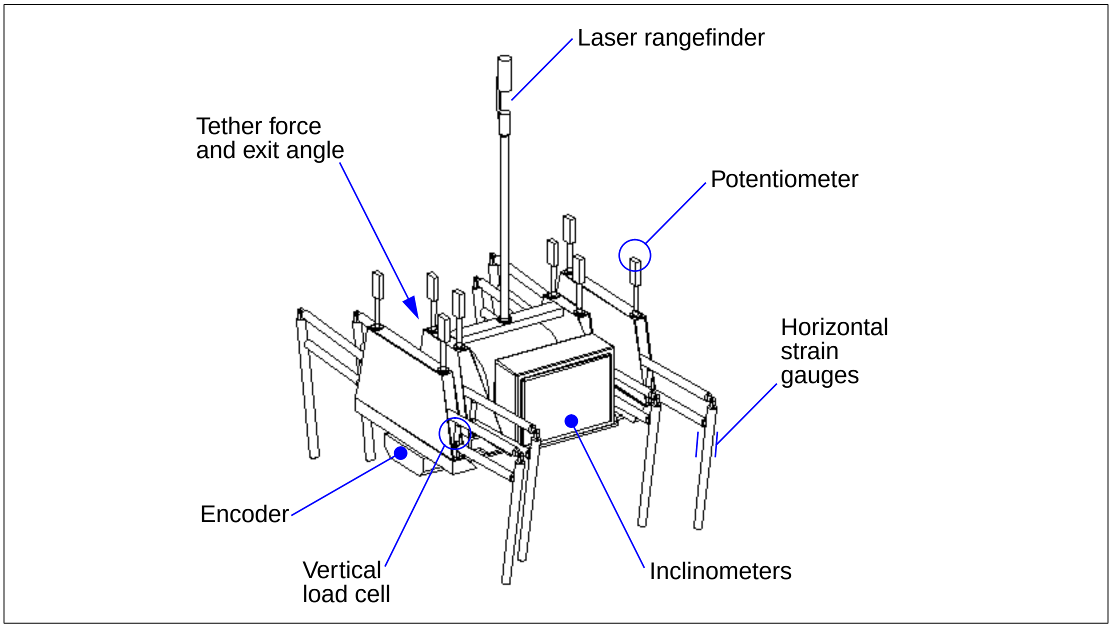

Figure 5-6: Dante II sensors

Computing and tethered telemetry

Dante II's missions require both supervisory and direct control. Its operator interface allows automatic functions to be disabled and direct teleoperation to take control. [Fong95] The need for variable control modes motivated the selection of general-purpose computers and motion control boards.

The on-board computing hardware includes three processor boards. Real-time control is distributed among the three processors, which all run a multi-tasking operating system. The first processor collects sensor information and writes state into shared memory at 120 Hz. The second processor drives eight leg servo loops and services motion control boards for the translation, turn, and tether actuators. The servo loops generate trapezoidal velocity profiles from leg encoder values at 150 Hz to produce smooth motion. The third board runs the gait control processes which can access sensor values and servo-loops. It has cycles available for other functions, including external communication.

The on-board computers communicate off-board via a tether and satellite uplink. The tether is composed of a video coaxial cable and several twisted-pairs, surrounded by load-bearing fibers. It provides power, communication, and physical support. The satellite uplink is 192kb with a round-trip delay of about 4 seconds. This is sufficient for monitoring robot state, although transmission of large data packets and network anomalies can cause delays of 30 seconds or more. As with most remotely-controlled systems, the telemetry encourages minimizing communication and maximizing on-board self-reliance.

Implementation of behaviors for Dante II

The gait controller for Dante II is built of 25 asynchronous processes including eight `contact foot` behaviors to stand, `roll`, `pitch`, and `clearance` behaviors to posture, `move frame` and `turn frame` behaviors to propel, eight `free foot` behaviors to step, one each of `raise legs`, `advance frame`, `lower legs`, `and sit still` to sequence walking. These specific behaviors were formulated to provide all the capabilities necessary for walking and are one of many effective designs that follows the principles previously described.

Behaviors produce standing, posturing, propelling and stepping

There are eight `contact foot` behavior processes; one for each of the eight legs. The `contact foot` behavior causes the foot to maintain contact with the terrain, and acts to lower the foot to the ground whenever a vertical force is not sensed. When exhibited, the `contact foot` process inhibits the action of `move frame` and `turn frame` processes. The emergent behavior is a reflex that returns the foot to the ground if it loses contact and a coordination with body motions to interrupt translation and turning until contact (and stability) is reinstated.

A graphical representation of a `contact foot` behavior process is depicted in Figure

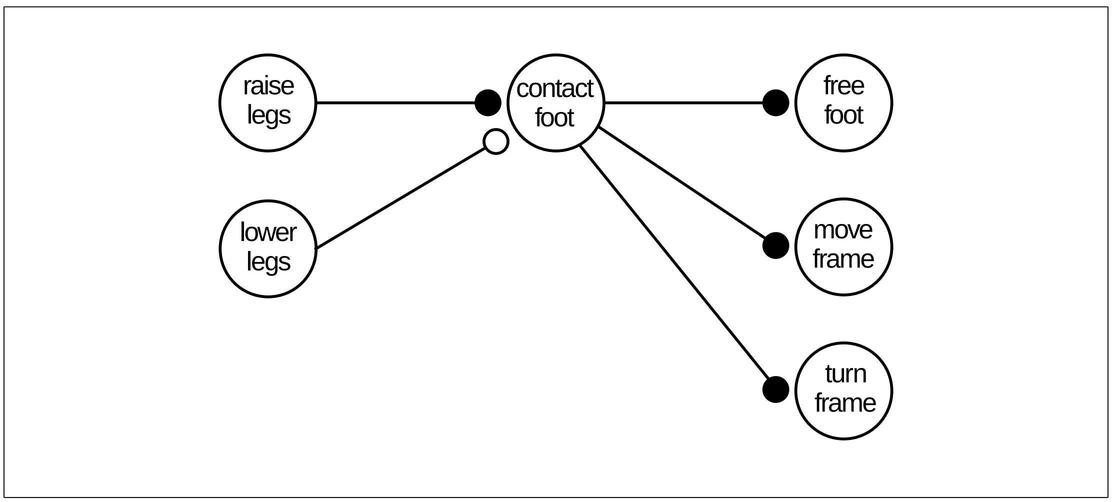

Figure 5-7: The contact foot behavior for each leg is exhibited when the legs of its frame lower. It it always inhibits the free foot behavior of the same leg and inhibits the move and turn frame behaviors when it does not detect contact with the terrain.

5-7. In this diagram, inhibition and exhibition links relative to the single behavior (in this case `contact foot`) are shown but the links between other behaviors and the entire extent of the activation network are not. Exhibition links terminate in an open circle and inhibition links in a closed, black circle. These links are asynchronous and are activated based on specific conditions—they are not always active when the central behavior is exhibited nor are they activated in a fixed sequence.

`Contact foot` senses leg position and vertical force. It causes the foot to lower until a force threshold has been crossed. `Contact foot` produces a position servo reference for the leg's vertical actuator. It also sets an appropriate velocity and acceleration.

Gorinevsky developed an active control system to accommodate ground compliance and sinkage while walking in soft soils. [Gorinevsky90] The reliability of predicting the legs' moment of ground contact is crucial to determining compaction and considerably influences the quality of the compensation. This argues for precise servo control.

The `clearance` behavior maintains distance between the body and the terrain. It monitors the average extension of all legs in contact with the terrain as an approximation of ground clearance. Whenever the value exceeds acceptable bounds, `clearance` inhibits the `roll` and `pitch` behaviors and commands all legs (both recovering and supporting) to raise or lower to the desired ground clearance.

To correct for rolling terrain, the `roll` behavior adjusts robot posture about the longitudinal (Y) axis. Typically roll is minimized in order to maximize stability, although in some situations it is reasonable to lean to one side. A coordinated motion of all legs—some raising, some lowering—rolls the robot to the correct value.

On level terrain, the `pitch` behavior could function identically to the `roll` behavior: monitoring an inclinometer, measuring the pitch about the lateral (X) axis, and coordinating corrective leg motions. However, Dante II climbs slopes and must follow the pitch of the terrain. By fitting a plane to the position of all the supporting legs, a coarse estimate terrain-relative pitch can be made proprioceptively. A large object under one foot can bias the pitch estimate (and clearance estimate) but adjusting to surmount the obstacle is not harmful. With the `pitch` behavior estimating relative body-terrain pitch, Dante II can negotiate transitions between differing slopes.

Initially, the `clearance`, `roll`, and `pitch` behaviors were exhibited only during times when all eight legs supported, but we found that posture adjustments during body translation are acceptable, and reduce the step-cycle period. It is not uncommon for Dante II to roll, pitch, and raise or lower (in any order) during the course of one body translation.

Converse to the `contact foot` behavior, the `free foot` behavior causes the foot to stay free, out-of-contact with the terrain. It is depicted in Figure 5-8. When exhibited

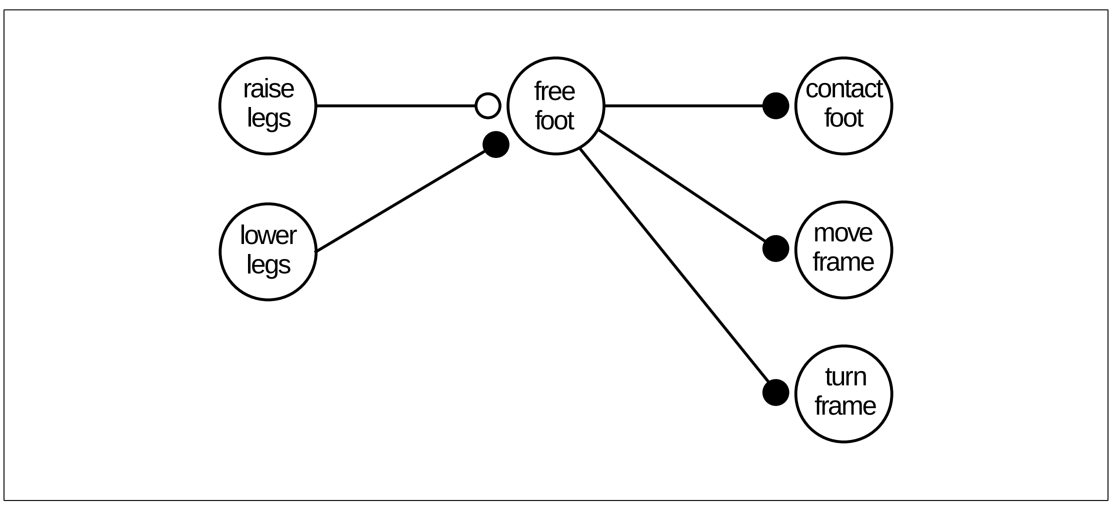

Figure 5-8: The free foot behavior for each leg is exhibited when the legs of its frame raise. It it always inhibits the contact foot behavior of the same leg (they are mutually exclusive) and inhibits the move and turn frame behaviors when it detects contact with the terrain.

and detecting either vertical or horizontal terrain contact, `free foot` raises the leg. While freeing the foot, the `free foot` process sends inhibition signals to `move frame` and `turn frame`. `Free foot` also inhibits the `contact foot` behavior of the same foot, since the leg should not simultaneously be attempting to break and maintain terrain contact.

The free foot behavior is comparable to tactile reflexes observed in animals, cats and locusts for instance, to lift the leg above an object contacted during recovery.

There is a cumulative effect—a reflex that causes legs to raise up when a leg bump occurs, coordinated with a momentary pause in body motions.

The `move frame` and `turn frame` behaviors translate and rotate (respectively) the recovering frame of legs. They may be inhibited during the course of their action, but when exhibited again will seek to drive the frame to the proper configuration. The intention of a behavior persists as long as it is active. In a hierarchical planning approach, motion commands are generated, but if some intervening condition causes their failure, the intention to move is gone. The command must be issued again, typically as the result of a replanning activity. When the intention to place a foot on the ground is established, a behavior will keep trying to achieve and maintain that intent. What happens is that the frequent interruptions that occur during walking do not interfere with the robot reaching the desired state.

A group of behaviors: `raise legs`, `advance frame`, `lower legs`, and `sit still` when sequenced together, enable walking. They are shown as a cycle in Figure 5-9.

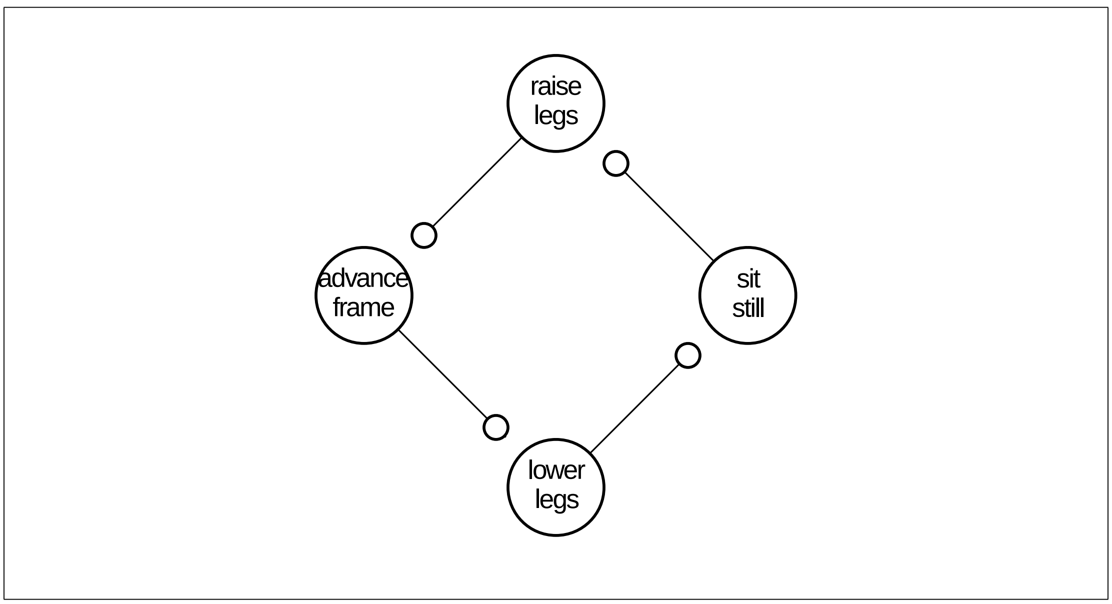

Figure 5-9: Raise legs, advance frame, lower legs, and sit still operate in a cycle of exhibition.

The `raise legs` behavior, diagrammed in Figure 5-10, coordinates the lift of a group of legs. It sends an exhibit signal to a set of four `free foot` processes that it maintains until all four have raised. It then sends simultaneous exhibition signals to the `advance frame` behavior.

The `advance frame` behavior exhibits the `move frame` and `turn frame` behaviors concurrently and monitors frame position until all desired conditions are met. It is shown in Figure 5-11. They then signal `lower legs`, shown in Figure 5-12, which signals `sit still` (for image and data capture), and completing the cycle, `raise legs`

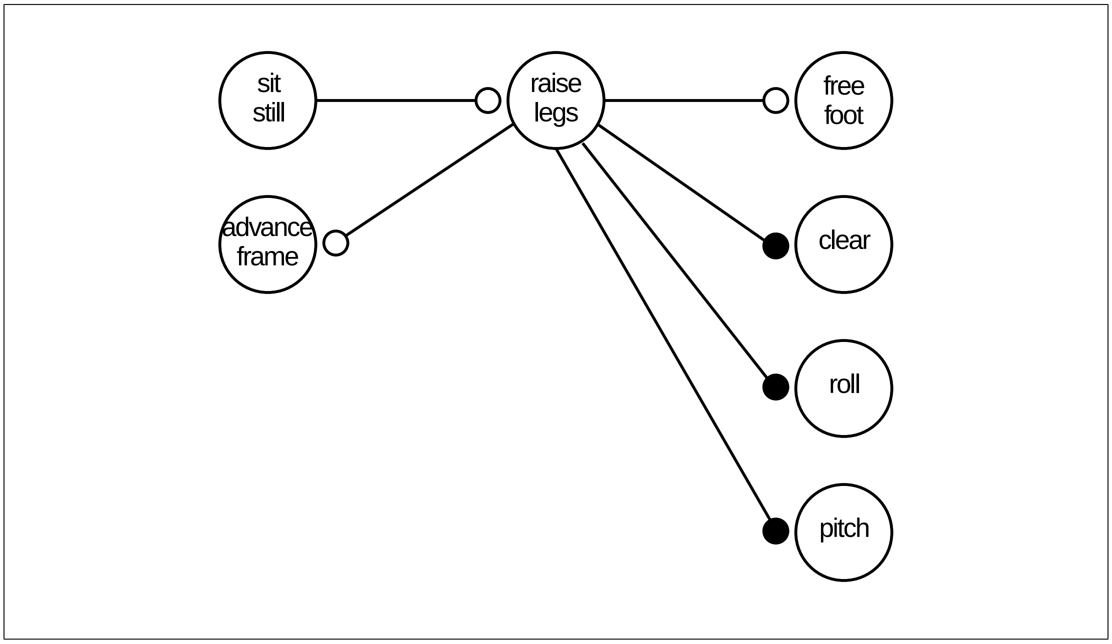

Figure 5-10: The raise legs behavior exhibits the free foot behaviors for a frame of legs and temporarily inhibits the clearance, roll, and pitch behaviors while the legs break contact with the ground. When all the legs on the frame are free, the raise legs behavior sends an exhibit message to the advance frame behavior.

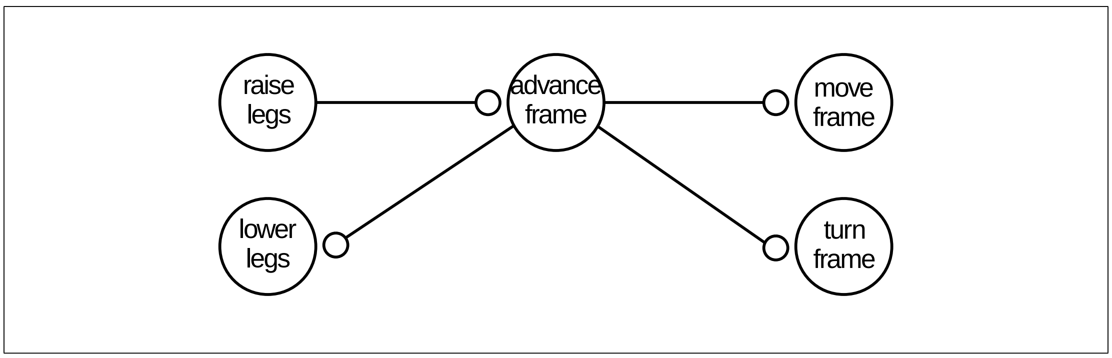

Figure 5-11: The advance frame behavior exhibits both the move and turn frame behaviors, which concurrently translate and rotate the frame. It then sends an exhibit signal to the lower legs behavior.

again. The `sit still` behavior occurs when all legs are on the ground and indicates the time at which frames swap support. It provides a period during which the machine is at rest and vibration-free images can be captured. The duration of `sit still` can be reduced to zero to provide continuous walking motion.

Behaviors interact with servo loops

To posture requires coordinated motion of the all legs—even non-supporting legs must adjust so that they are not driven into the ground. The legs simultaneously effect a new pitch, roll, or clearance from the terrain. The `clearance` behavior maintains distance between the body and the terrain by monitoring the average extension of all supporting legs. To accommodate rolling terrain, the `roll` behavior adjusts robot posture with respect to gravity about the longitudinal axis. The `pitch` behavior acts similarly about the lateral axis but fits a plane to the position of all the supporting legs to estimate terrain-relative pitch (objects under a single foot, which bias the estimate, are still

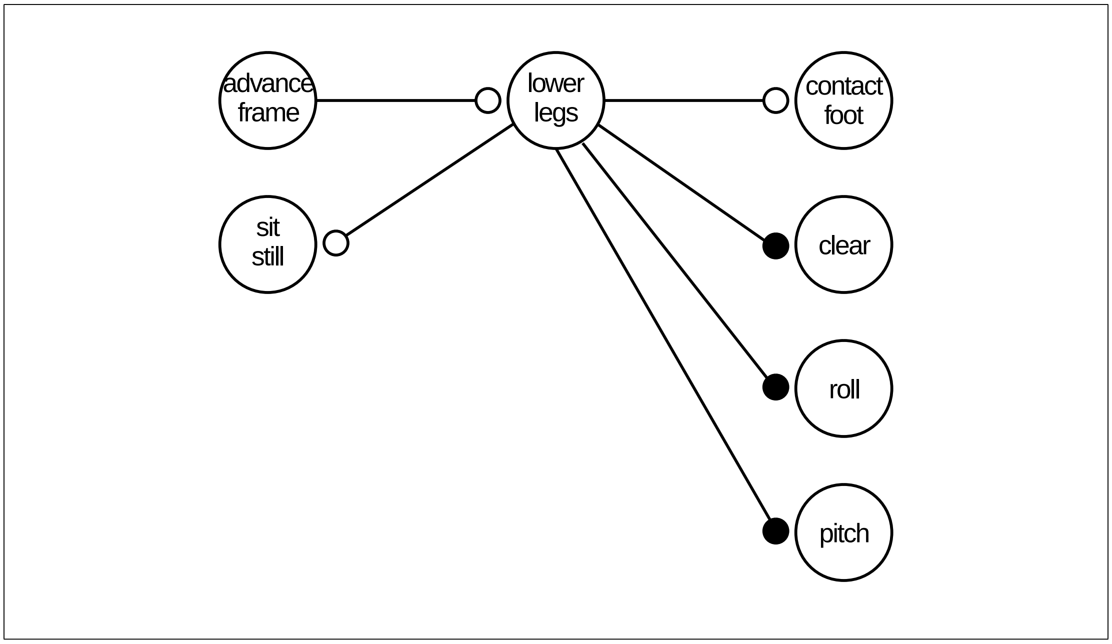

Figure 5-12: The lower legs behavior is exhibit as advance frame completes body motion. The lower legs behavior exhibits the contact foot behavior for a frame of legs. Until ground contact is established, clearance, roll and pitch behaviors are inhibited.

acceptable motivation for a pitch adjustment). In Figure 5-13, these three behaviors contribute increments to the servo reference.

To step, a leg must stop seeking ground contact and start avoiding it. The `free foot` behavior causes the foot to stay free, out of contact with the terrain and also inhibits the `contact foot` behavior of the same foot, since the leg should not attempt to both break and maintain terrain contact.

When detecting either vertical or horizontal terrain contact, `free foot` inhibits `move body` and raises the leg (by changing the servo reference). The inhibition of body motion persists until the foot is free of the terrain. The cumulative effect is a reflex that causes the robot to stop and raise a leg when a bump occurs. The reaction time is less than 0.5 seconds which has proven adequate in actual operation. [Wettergreen95] Other walking robots including Genghis [Brooks89] and animals like the locust [Pearson84] employ a similar reflex.

To walk, legs must be freed of the terrain, recovered to a new position while the body advances, and then placed back on the ground to support while other legs step. Three behaviors: `raise legs`, `advance frame`, and `lower legs`, do not provide servo references but instead sequence walking by inhibiting and exhibiting other behaviors. The `raise legs` behavior coordinates the lift of a group of legs. It sends an exhibit signal to a set of `free foot` processes and then, once the legs are free, sends an exhibit signal to the `advance frame` behavior, which controls the body position servo reference, and in turn signals the `lower legs` behavior, completing one step cycle.

Figure 5-13 depicts behaviors as they contribute to the leg position servo reference.

Dante II’s nominal gait, shown in Figure 5-14, is the result of coordinating behaviors.

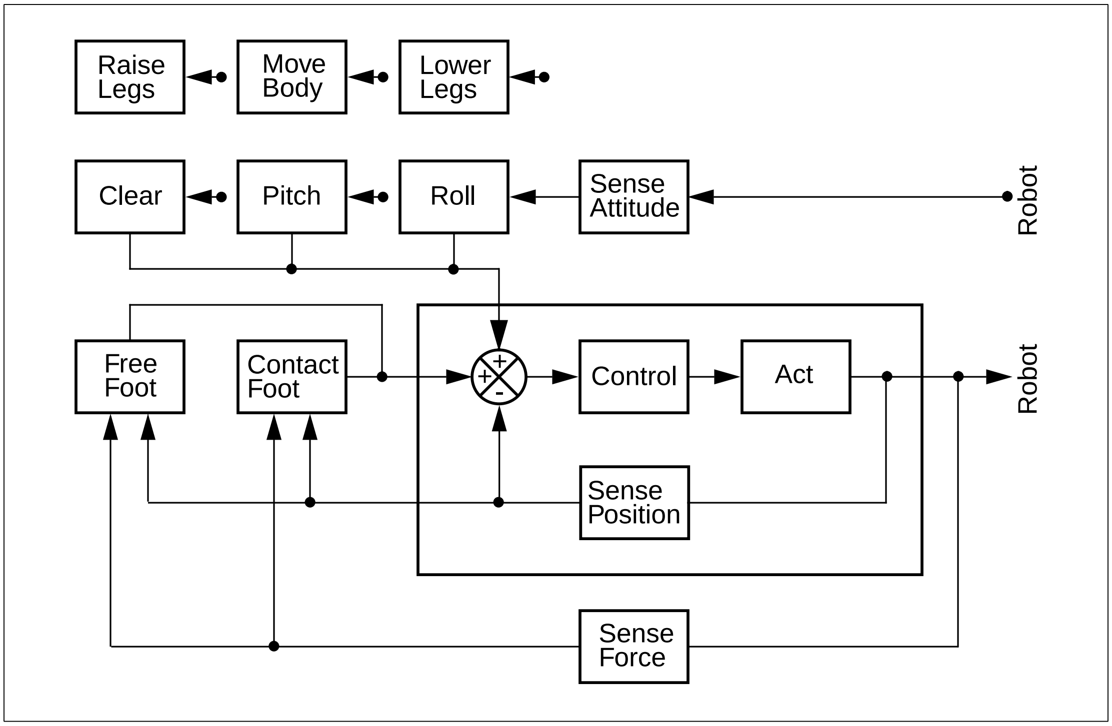

Figure 5-13: A schematic overview of the behaviors as they control motion by adjusting servo reference values. `Free` and `contact foot` behaviors are mutually exclusive and trade production of a servo reference. `Roll`, `pitch` and `clearance` behaviors sense body attitude and incrementally adjust the servo reference.

Performance by Dante II

Dante II underwent two long duration tests (in Pittsburgh and in Anchorage, Alaska) before operating in Mount Spurr. These tests indicated that Dante II could walk stably and with an average speed around one-half meter per minute.

At the Pittsburgh slag heaps

The Pittsburgh slag heaps are expansive slopes of hardened slag, a by-product of steelmaking. We conducted tests along a 170m path. The upper portion of the path is level for 40m, and then slopes into a smooth escarpment of 30-40° for 70m and 40-50° for 5m, and then follows a moderate but trenched uphill grade for 60m. Operators teleoperated Dante II in areas of slope transition.

The longest autonomous run was 182 steps over 111m in 219 minutes (3:39) for an average speed of 0.51 m/min. The slope varied from 30° to 40° and the cross-slope (lateral to the direction of travel) was ±5°. Roll and pitch were maintained to within ±2°.

Dozens of leg bumps occurred during these tests and the reflex (`free leg` behavior) was so effective that accurate specification of leg lift height was unnecessary; feet could skim the ground, providing protection against tipping, and raising up if they bumped. The reactions occurred so quickly (on the order of 0.5 seconds) that body advance slowed almost imperceptibly.

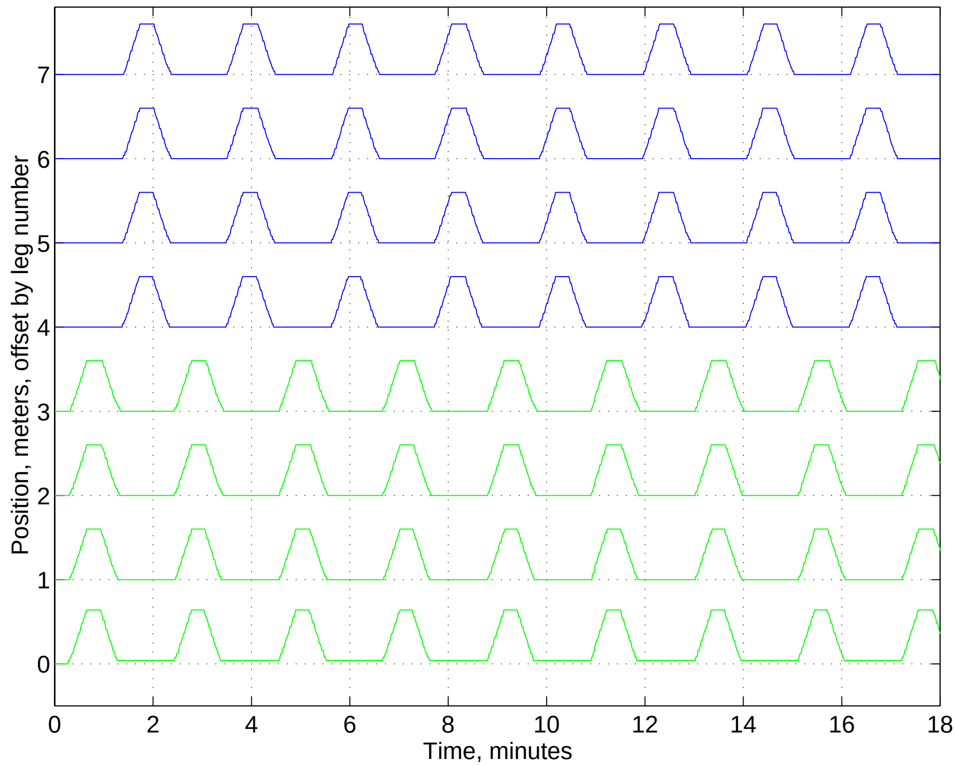

Figure 5-14: Dante II's nominal gait. This gait timing diagram is a composite of the vertical elevation of each of the eight legs. The vertical elevation, the height, of each of the legs is offset by one meter and streamed across the diagram. The gait, an alternating tetrapod, is a repeating cycle in which the legs of each frame (inner frame legs 0,1,2,3, and outer frame legs 4,5,6,7) raise up, hold during the frame advance, lower down, and maintain support. This timing diagram depicts the gait as it appears on flat terrain without obstacles or adjustments to posture.

Early in the testing program for Dante II we discovered how difficult and exhausting it is to teleoperate a walking robot. Having the robot walk autonomously is faster and with fatigued operators, more reliable.

At an Anchorage gravel pit

In Anchorage, Dante II was tested in a gravel quarry. The site had a moderate slope, on average 30°, with sandy soil eroded with 10-50cm ruts. The path of descent and ascent was 92m. From the top, the slope descends approximately 50m before it abruptly transitions to a level bench. From this bench, it again drops (to 30°) for 5m and then slowly transitions to level over 30m.

The descent into the gravel pit was primarily teleoperated, although brief portions were autonomous. The descent required 321 minutes (5:21) for an average speed of 0.28 m/min. This speed is less than half the maximum speed dictated by the motor/amplifier configuration and is attributed to human delays in interpreting sensors, considering information, and making plans. When ascending the same terrain autonomously (Figure 5-15), it took 179 minutes (2:59), the gait controller averaged 0.51m/min, and in some areas averaged 0.67m/min—more than twice the human-teleoperated speed.

The ascent did require one instance of operator intervention: the first step above the level bench onto the 30° slope was placed in a depression, masking the imminent uphill

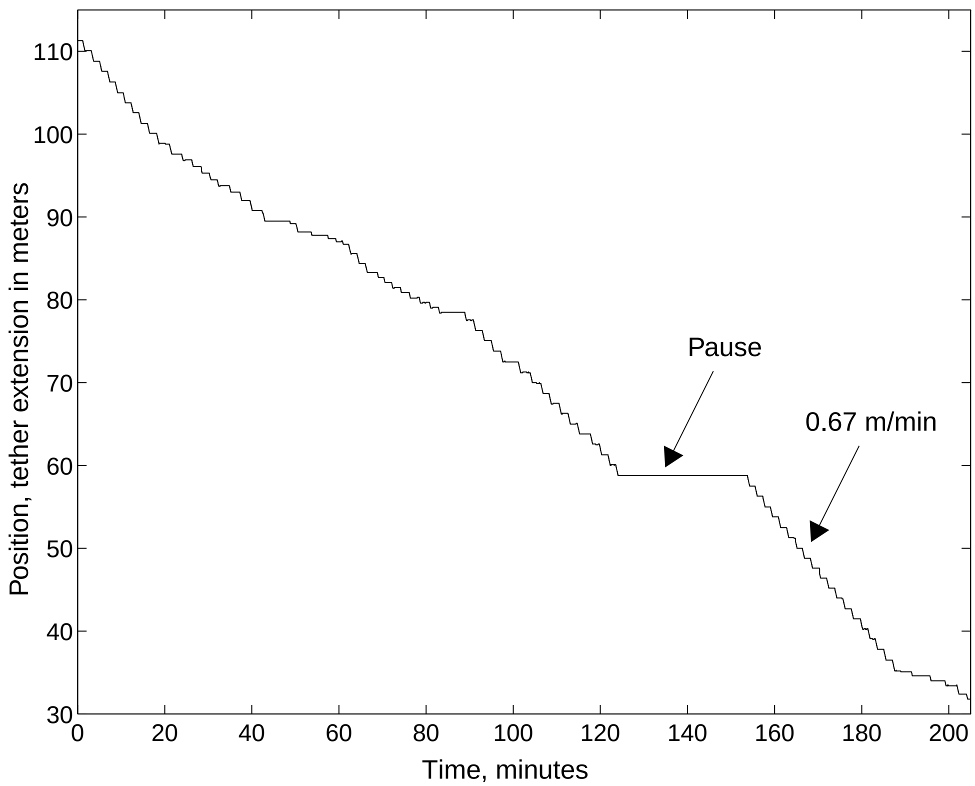

Figure 5-15: Autonomous ascent in the Anchorage gravel pit. Dante II ascended up and over benches, adjusting its pitch to the underlying terrain. The average speed, excepting the pauses (for television reporters), is 0.51 m/min and the maximum sustained speed is 0.67 m/min.

transition. The pitch correction required in the next step would have exceeded 20° (which is physically stressful to the mechanism) and was divided over two steps. This instance of shortsightedness points out the need to foresee some situations and prepare in advance. (I will address this later in the thesis.)

In Mount Spurr's crater

Mount Spurr's active crater is on a secondary peak, Crater Peak, at elevation 2300m. One side of the crater is comprised of a 350m vertical wall with talus slopes at the base. The other side is blown out, with a broad flat rim and a 20-45° slope down to the crater floor. Dante II descended 200m to the crater floor. The slope is covered with snow, wet ash, and mud, which are deepest in the middle of long chutes that run downhill. Ridges divide the chutes and like the crater floor, are littered with meter-size blocks. Fumarole vents of interest are located on the crater floor.

Because it was necessary to navigate across the chutes and ridges, Dante II experienced cross-slopes up to 30°. This severity was unexpected. The idea was to travel directly downslope as much as possible, but the robot reached dead ends that had taken hours or days to discover. The most direct exits were to turn across the slope and climb over a ridge into the next chute.

On the upper snowfield

On the upper slopes of the crater Dante II walked autonomously twice: 9.80m in 23.30 minutes (0.42m/min) and 9.60m in 19.78 minutes (0.49m/min). Shown in Figure 5-16, this is about twice the typical speed of teleoperation.

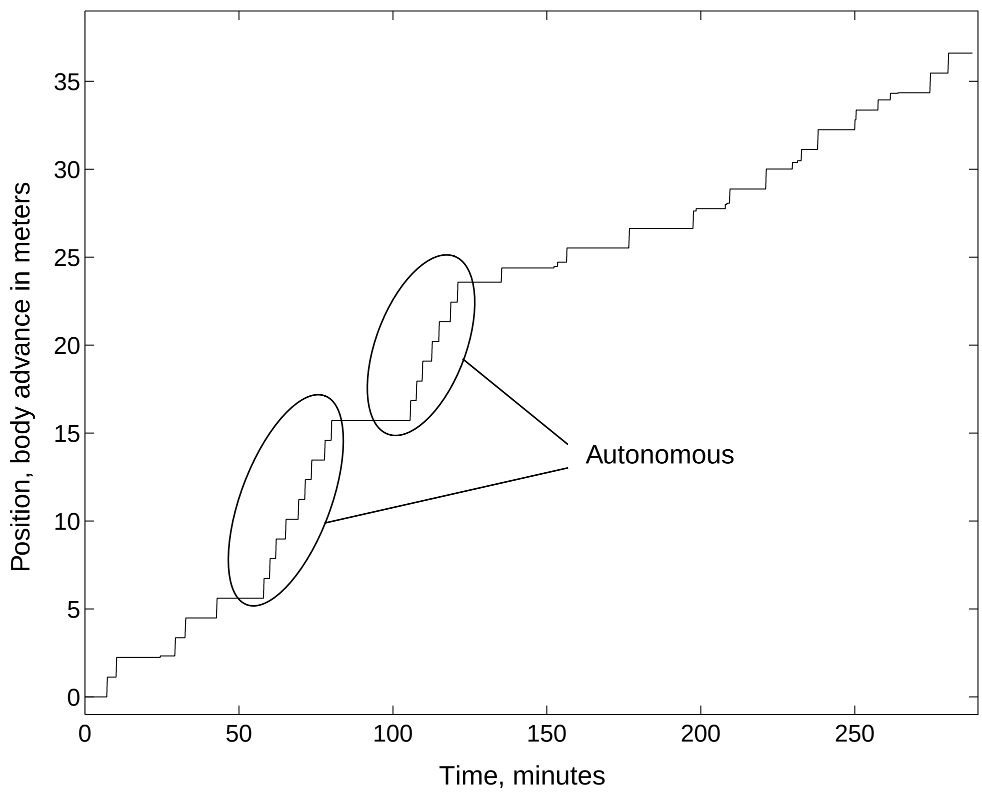

Figure 5-16: Autonomous walking on Mount Spurr's upper slopes. The first autonomous segment begins after 60 minutes and runs 23 minutes with an average speed of 0.42 m/min. The second autonomous segment begins after 105 minutes, and runs 20 minutes with an average speed of 0.49 m/min. The autonomous speed is about three times faster than direct teleoperation by an experience human operator, seen in the remainder of the recorded data.

The first autonomous segment of the descent occurred in a chute of old consolidated snow; it had a tough crust but compacted as legs loaded. Dante II crossed the chute on a diagonal, dropping cross-slope to its right. Figure 5-17 presents data recorded during this first segment. It depicts the vertical extension, the height of each of Dante II's eight legs on a different line, over a period of time. In groups of four legs (legs 0,1,2,3 and 4,5,6,7) legs raise up, hold in the air during body motion, and then lower down to support. (Refer to Figure 5-5 for leg numbering convention.)

While walking in the hard-packed snow the robot repeatedly raises up. As each frame lowers it meets supportive resistance as it encounters the snow, but before reaching the nominal leg extension. The leg descent stops (doing otherwise would tip the robot) but when the alternate frame raises, the robot sinks into the snow. The body clearance is corrected by further extending the legs. At about minute 59 all legs simultaneously lower including legs 4,5,6,7 which are free of the ground. This happens again at minute 61. At minute 62 the front of the robot pitches up as the front legs (0,2,4,6) lower and

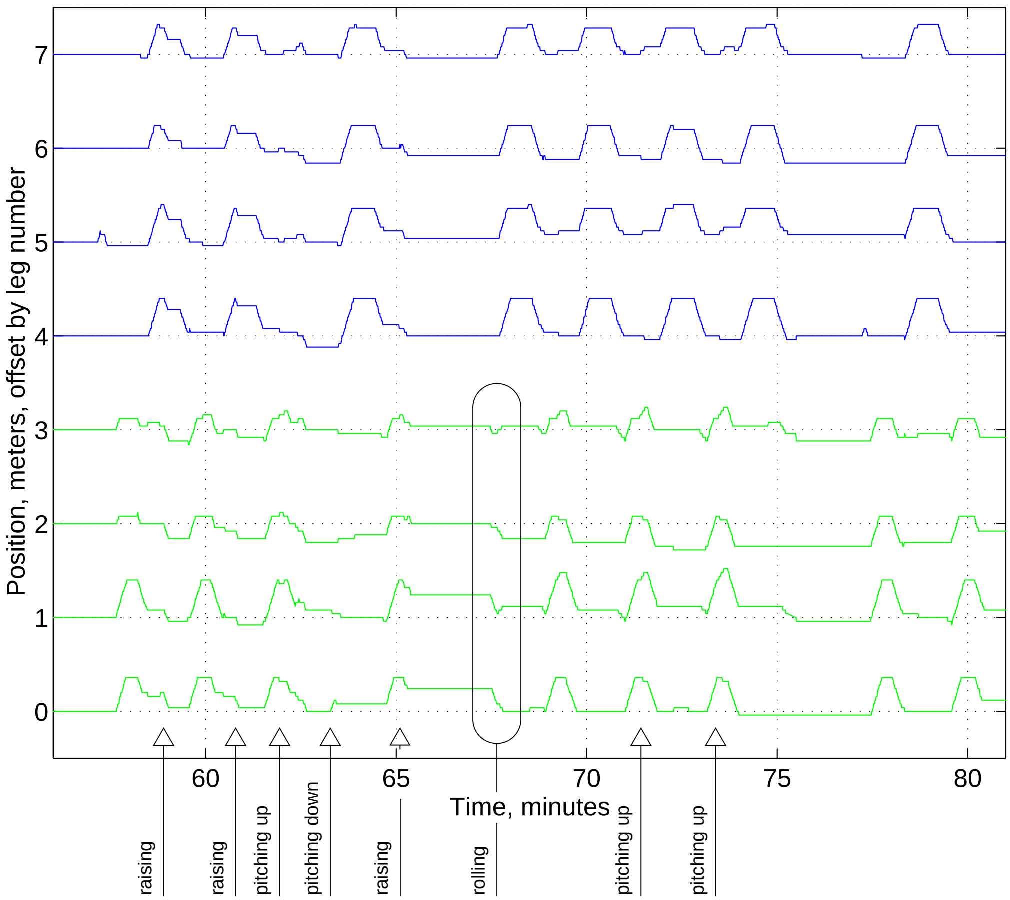

Figure 5-17: Dante II descending a snowfield on Mount Spurr's upper slopes. The vertical position of each of the eight legs (inner frame dotted) plotted against time. While walking in this hard-packed snow the robot repeatedly raises up—as each frame lowers it meets supportive resistance, but when the alternate frame raises, the robot sinks into the snow. The body clearance is corrected by lowering the legs. At minute 67 legs 0,1,2,3 lower and then roll while legs 4,5,6,7 are in the midst of lifting off for a step.

the rear legs (1,3,5,7) raise. The pitching behavior occurs in response to a perceived difference between the slope pitch and body pitch. The correction is made as the outer frame is in the air. After it lowers to support, the upward pitch adjustment is perceived as too great (this likely due to compaction of the snow under the rear legs as the weight shifted to the back) and so a slight pitch adjustment is made to bring the front end down. At minute 65 the body raises as before. In an atypical example of rolling, at minute 67 the inner frame legs (0,1,2,3) lower to the ground and then roll the body while the outer frame legs (4,5,6,7) are in the midst of lifting off for a step. At minutes 71 and 74, Dante II pitches the front end up, as the slope of the terrain is apparently decreasing.

Examining the chart as a whole, notice that on average the right-side legs (2,3,6,7) raise up less during stepping than the left-side legs. This is most apparent on legs 2 and 3 and is because the right-slide legs are upslope of the left-side legs. The effect is not as pronounced as the true cross-slope would justify because the human operator has reduced the lift-off of the downslope legs. At a later time, the cross-slope became so extreme that downslope legs 0 and 1 were at maximum extension while upslope legs 2 and 3 could barely clear the terrain at minimum extension. Another gross observation is the behavior of leg 3, the inner frame, right, rear leg, between minutes 68 and 73. During this period outer frame sets down three times and each time seems to lift leg 3 out of contact with the terrain. The `contact foot` behavior of leg 3 is activated and it independently lowers to regain contact (and then subsequently is triggered to step) and raises up again.

The second autonomous segment took place on the downhill side of the same snow chute as the first segment, as the deep snow shallowed and transitioned into a low rocky ridge. The vertical position of the legs is recorded in Figure 5-18.

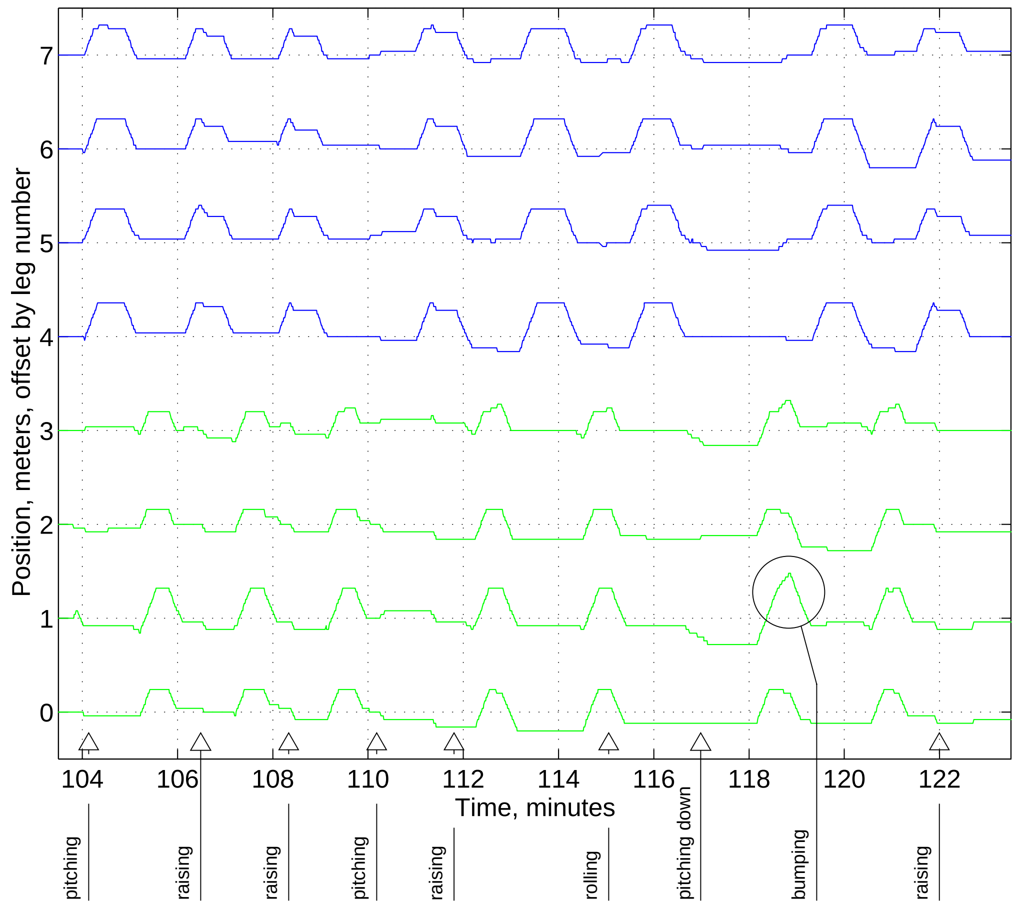

Figure 5-18: Dante II descending Mount's Spurr upper slopes at a later time than Figure 5-17. The steepness of the slope is decreasing so the robot pitches its front upward. At minute 119, leg 1 bumps a rock and continues to raise up until it breaks free. A slight pitching move occurs simultaneously.

As the slope decreases Dante II's posture is nose down into the ground. It must repeatedly raise (as near minutes 106, 108, and 112) to maintain proper clearance. The pitch also adjusts, pulling the front end up at minutes 104 and 110, and avoiding further reduction of clearance. At minute 110 all eight legs are on the ground and it is quite clear the front legs (0,2,4,6) move down, and the rear legs (1,3,5,7) move up. Later, at minute 115, a slight correction to the roll occurs (only apparent on legs 3,4,5,6,7 because of scale).

At minute 119 the bump reflex is clearly demonstrated. Previously, at minute 117 the body pitched down; the inner frame legs stepped forward over a hump and detected an increase in steepness. Then as the outer frame advances a rear leg, leg 1 contacts the hump and begins to raise up. The reaction time is less than 0.5 seconds. Almost simultaneously Dante II pitches the front end upward. There is possibly a slight contact with leg 3 which also responds by raising concurrent with the pitching motion.

Comparing the duration of the frame advance (which occurs when legs are raised) of inner and outer frames, it is evident that the inner frame advance takes longer. This is because the tether is attached to the inner frame and must be spooled out as it advances. This spooling, which is force-controlled with a position feedforward term, is slower than the nominal advance which is possible by the outer frame.

On the lower slopes

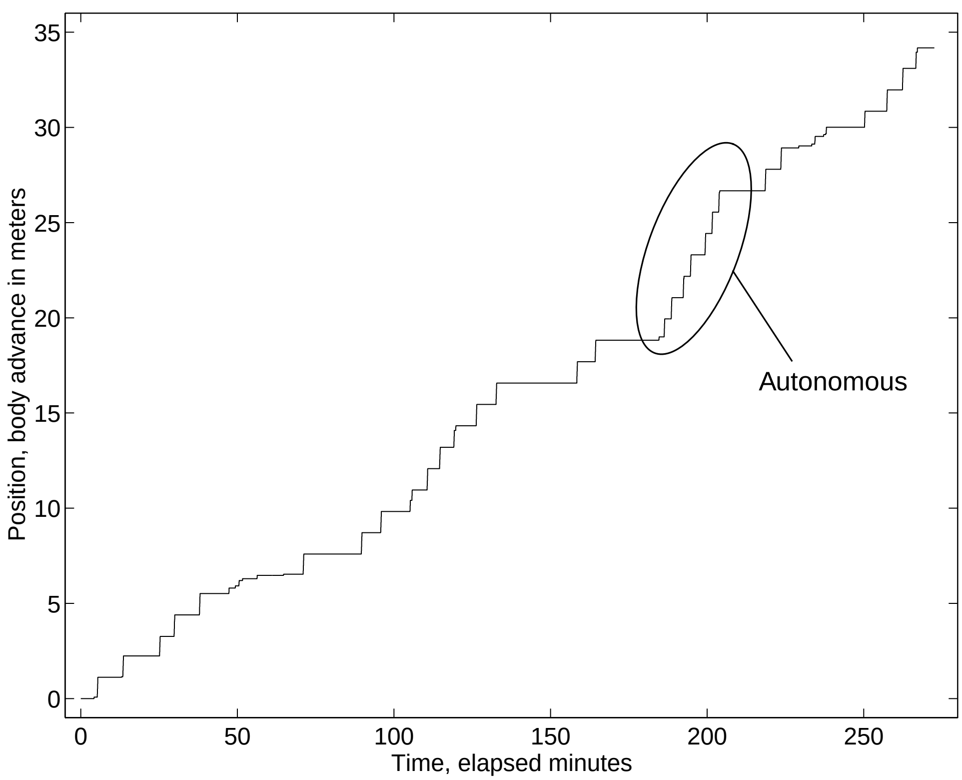

Figure 5-19: Autonomous descent on Mount Spurr's lower slopes.

Approaching the crater floor, Dante II made two more autonomous descents down a snow chute, 8.3m in 35.2 minutes (0.24m/min) and 6m in 12.3 minutes (0.49m/min). Performance on the third autonomous segment appears in Figure 5-19. The terrain was composed of solidified snow and ice with rocks lying on its surface. The rocks, which were uncovered by snow melt, were easily cleared or sent tumbling when bumped. This was again an area of substantial cross-slope. The vertical positions of the legs are recorded in Figure 5-20.

A communication interruption occurred at minute 189 just as the inner frame began to raise. Motion halted after several seconds without communication and resumed to reveal the legs partway raised (step change). Because of the cross-slope, icy terrain and

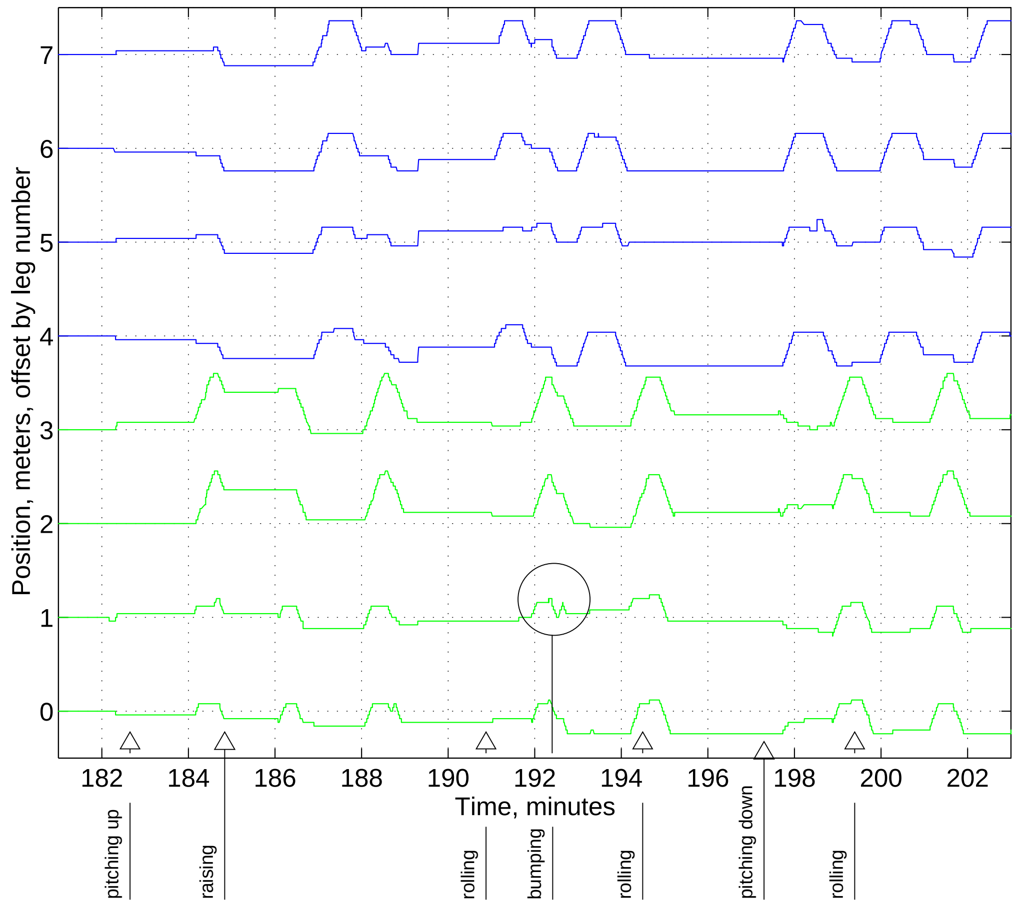

Figure 5-20: Dante II descending the lower slopes in Mount Spurr's crater. This area of terrain has a substantial cross-slope and because an unfavorable tether exit angle Dante II slipped across the slope. Repeated roll maneuvers correct the tip. At minute 192, Dante II lowers all legs in order to raise up. Leg 1 lowers as the body raises to maintain its position but (probably because of settling) detects contact and independently raises up until it is free.

an unfavorable tether exit angle which induced a yawing moment, Dante II slipped across the slope as it walked. Repeated roll maneuvers corrected the resulting tip at minutes 191, 194 and 199. At minute 192, Dante II lowers all legs in order to raise up. Leg 1 lowers as the body raises to maintain its position but (probably because of settling) detects contact and independently raises up until it is free. Several extended pauses occur during operation to allow laser scanning to occur.

Data for the fourth autonomous segment was not retained. The performance, which was in softer terrain of snow and rock, was short (6m) and fast (0.49m/min) by comparison.

In Figure 5-21, Dante II surmounts a small knob with extreme cross-slope to reach a fumarole on the crater floor.

On the return ascent

The ascent from the crater was hampered by snow melt, mud, and freshly-exposed obstacles. Dante II did not walk autonomously during its ascent, instead it was

Figure 5-21: Dante II on Mount Spurr's crater floor

teleoperated by human operators until about 100m from the rim, where it tipped over and had to be rescued by airlift.

It is important to understand that during teleoperation Dante II's posture is not automatically adjusted—the operator must monitor roll and pitch and command appropriate corrections. The circumstances of Dante II's tip-over, while not caused by the behavioral gait controller, illustrate why reactive approaches are appropriate and how, had they been engaged, the tip-over might have been avoided.

At the time of its tip-over, Dante II stood on a 30° cross-slope with its right legs upslope, its left legs downslope, and its body rolled down with the slope. Its tether exerted a transverse force leftward, in the downward direction of the cross-slope. As the legs of the free frame lowered to support, they could not obtain sufficient reactive force from the ground to indicate support. What force they did apply occurred first on the right, upslope side and exacerbated the roll. This may have also slackened the tether causing it to increase tension, which increased the cross-slope force component, which further increased the roll down to the left side. It was literally teetering on the edge.

The legs lowered slowly. Video footage reveals the supporting legs sliding down the cross-slope to the left and then, quite gently, Dante II falling onto its left side. All systems, including computing, video, and even the eight legs, remained operational.

How could this have been avoided? First, the posture maintaining behaviors should always be active. If the body were level initially and actively leveled as the frame placed and as it slid slowly downslope, Dante II would not have been teetering—its center-of-gravity would have been well within the support polygon, with a much larger stability margin. Still, the situation was dynamic in that the supporting legs slid downhill and the vehicle gained some inertia; perhaps it never would have regained static equilibrium.

Evaluating performance

At this point, quantitative justification that the walking performed by Dante II is robust and productive is unattainable. Only qualitative arguments are available.

Is it productive?

Referring back to Table 4-1 it is clear that Dante II is not the fastest walking mechanism —a turtle is 10 times faster, on average. Still, it has achieved speeds over 1.0 m/min on flat terrain (amplifiers specially tuned) and 0.67 m/min on rough terrain, the latter terrain contained pits and ridges of about half of Dante II's step height. The behavior-based gait controller produces continuous motion at the maximum achievable speed. In this sense, it is productive.

Is it robust?

Are the behaviors used to control Dante II intrinsically stable, barring any external influences? Some invariants:

- Legs are either free, contacting, or supporting
- A frame is supporting when all of its associated legs are supporting
- A frame is not supporting when one or more legs are free or contacting
- If no frames are supporting, then the robot may not be stable
- If one frame is supporting, then the robot is stable
- If both frames are supporting, then only one frame may change to not supporting
- Initially, one frame is supporting

Therefore, in walking the robot will always have at least one frame supporting, and will remain stable. Considering the gross motions of posturing, another invariant:

- If posturing the body, then all legs move simultaneously to maintain constant relative position and the center-of-gravity approaches the support polygon centroid.

Dynamic events or actuator limits can cause the robot to destabilize in spite of these invariants. For example, if the terrain breaks away under the feet, the robot may tip over before it can correct its posture. Any robot or control architecture could fail when confronted with catastrophic events or motions outside the normal operating regime.

The Petri Net shown in Figure 4-4 is an accurate model of Dante II's frame walking. That network (and by implication Dante II's controller) is live and safe. This means that all the states are visited and no state is a dead end, so the behavior activation network will not deadlock during the nominal gait cycle. But this is a limited model; it does not represent all the reflexes and in fact, deadlocks can occur. A leg raising because of contact with an obstacle will inhibit the forward progress of the body. If the leg cannot free itself, the robot will deadlock, needing operator assistance. The robot remains safe, but trapped.

The best that can be claimed is that the gait controller is internally robust and has demonstrated robust performance when subjected to external influences.

Summary

- Reactive methods map sensed conditions into actions, creating fast reflexes. Behavior-based methods restructure robot control from types of computations (perception, planning, control) to types of tasks (posturing or stepping). Rather than plan a gait, a viable sequence of leg and body motions can emerge from independently-controlled behaviors.
- A network of concurrent asynchronous processes modulate servo control of motions and interact to produce safeguarding reflexes and coordinated, aperiodic gaits.
- Direct teleoperation of a walking robot is tedious; supervised teleoperation results in faster, more reliable performance, so each behavior is parameterized so that external influence can be exerted on the character of its action (for example, the height the legs raise).
- No visual sensing is needed for Dante II to walk through rough terrain. It maintains steady progress as legs conform to the terrain, bumping obstacles, and the body pitches and raises to maintain the desired posture. Dante II descended into the crater of a volcano, at times walking autonomously at rates up to 0.5 m/min.

Chapter 6

Generalizing behavior to multiple gaits

In **Generalizing behavior to multiple gaits** I begin by looking at how animals walk. There are two purposes for this. The biological system of controlling walking has evolved through natural selection and by understanding that development, we can identify structures, patterns, and natural behaviors that are instructive to the development of walking robots. On the other hand, evolutionary pressures have not shaped animals exclusively for efficient walking, instead many other functions are relevant. I will try to distinguish fundamental differences between a robot and a cockroach, for example, and see where we need artificial solutions.

The performance achieved by Dante II generalizes to other walking robots. I will present a free-gait hexapod called SimPod. This robot is simulated using the same computing hardware as Dante II, but its kinematic structure is more complex, more flexible, and more like that of natural creatures. SimPod is capable of a variety of gaits seen in six-legged insects and can transition smoothly among them. Like Dante II, it can walk through rough natural terrain using only proprioceptive sensing.

Walking robots need to be able to perform different gait patterns to adapt their gait to different circumstances. The ability to switch gait patterns on-the-fly enables the robot to walk continuously, not stopping to shuffle its feet. Animals do this too; they use some patterns to walk quickly, others to walk slowly, and sometimes take one step at a time when exploring unknown terrain.

How animals walk

An explanation of how animals walk can come from either of two directions: bottom-up or top-down. Beginning with the fundamental components, muscle, nerve, and sensory cells, we can examine behavior in terms of the functioning of the nervous system. This is the physiological approach to explain the simplest cell, its interaction with other cells, their function as a group, and eventually the entire animal.

An explanation can also develop from the top, with observation of the overt behavior of the animal in its natural environment (or in restricted situations). We can quantify actions, look for patterns, develop models, and then hypothesize what mechanisms are necessary for behavior. Ethology is the study of naturally-occurring, unlearned behavior; psychology is interested in development and performance of behavior, primarily learned behavior. [Manning92]

Physiology and neurology of animal walking

From a physiological standpoint, walking behavior is a consequence of properly selected and timed muscle action. Muscles are enervated by impulses from nerves, so it is a neurological topic as well: how the nervous system produces the signals that enable walking.

Muscles move joints

Muscles are composed of fascicles, bundles of muscle fibers (cells), that shorten, produce tension, and pull on tendons and bones to move the joints. Muscles can pull but cannot push, so for reciprocal movements two muscles must be configured in opposition around a joint. Back-and-forth movement is caused primarily by the opposing extensor and flexor muscles, which increase and decrease joint angle. The dominant muscle alternates to change the direction of motion, while the opposing muscle maintains some resistance to maintain a particular compliance. Isometric contraction of the pair changes joint stiffness.

The force that a muscle can exert is proportional to its cross-sectional area, so although a square millimeter of muscle can exert only about 0.3 newtons, less force than a rubber band, stout muscles like the human hamstring can produce 4500 newtons of force. [Alexander92] This force decays over time as the muscle fatigues and relaxes.

The coordination, strength, and duration of muscle contractions has to be controlled and coordinated between antagonistic and cooperative muscle groups. This is the function of the nervous system.

Neurons transmit signals

The nervous system is composed of nerve cells called neurons. Most neurons branch into dendrites, which receive input, and a single axon, which carries output to various presynaptic terminals. The synapse is the gap between the presynaptic terminal of one neuron and the dendrites of another. Nerve cells conduct electrical impulses and bridge the synapse with chemical neurotransmitters.

Neurons are always electrically active and maintain a potential difference across their cell membrane, polarized so the inside is negative and the outside is slightly positive. This resting potential is the nominal ability of the cell to pass ions through protein channels in the membrane. Stimulating a neuron by an electrical or chemical signal causes a depolarization in the membrane that may be propagated. Propagation occurs when the depolarization, a postsynaptic potential, is strong enough to trigger an electrical impulse, an action potential, that travels down the axon.

Some action potentials are triggered by a single postsynaptic potential, others by a rapid series of subthreshold potentials that sum together, and still others by weak potentials from several sources that all arrive at the same neuron. Temporal and spacial summation results from a membrane acting as a capacitor to small impulses that are displaced in time or position.

Some kinds of neurotransmitters released into the synapse change the neuron's resting potential. This facilitates propagation by decreasing the threshold that presynaptic potentials must attain, or by causing larger postsynaptic potentials. Neurons do not just excite each other. Some neurons inhibit others by releasing neurotransmitters that hyperpolarize the postsynaptic membrane, making it less likely to respond.

Sensory neurons transduce physical properties

Sensory neurons transduce the physical properties of an animal and its environment into electrical signals. Their membranes are affected by light, temperature, chemicals, or force.

Some sensory neurons perceive the external environment. An example is the retina of the eye, which is composed of sensor neurons sensitive to light of a particular wavelength. There are also nerve cells that act as contact sensors, stimulated by direct pressure, or embedded in hair follicles and sensitive to movement of the hair.

Properties internal to the animal are also detected by sensory neurons. The legs of many insects contain chordotonal organs, which consist of a group of sensory neurons that encode the angle and rate of change of the femorotibial joint. [Zill93] Campaniform sensilla are receptors in the legs of insects that function like strain gauges. Their dendrites are embedded in the exoskeleton and the forces generated by the insect's weight and muscle contractions stimulate the neuron.

Motor neurons control muscle contraction

Motor neurons produce neurotransmitters that cause changes in effector organs, for example they release chemicals that cause muscles to contract or relax. Motor neurons extend into the muscle fascicles where they can initiate contraction by releasing neurotransmitters directly into the muscle fibers. They also cause muscle relaxation by releasing counteracting neurotransmitters that increase the stimulation necessary for contraction, thereby inhibiting it.

Interneurons modulate neural signals

Interneurons are nerve cells that affect the overall activity of a neural circuit by reversing the signal (from excitation to inhibition), by amplifying postsynaptic potential strengths, and by performing other modulations. Interneurons are commonly connected between sensory and motor neurons.

Interneurons may act to coordinate muscle action by reversing the excitory signal to one muscle and sending an inhibitory signal to another muscle. For example, in walking interneurons in one leg are responsible for inhibiting the muscles located on the opposite limb—when the flexors of one leg are contracting, the flexors of the other limb are inhibited from doing so. [Manning92]

Command neurons carry signals from higher brain centers

Command neurons connect higher brain centers to other sorts of neurons. They are often involved in exciting part of a neural circuit that initiates some behavior or in exciting an interneuron that inhibits some action.

Pattern generators produce rhythm

Central pattern generators (CPGs) are neural circuits that are believed to produce the underlying patterns of rhythmic motor activity. [Grillner85] CPGs may employ pacemaker cells, which are capable of rhythmic bursts, or network oscillators, which produce rhythmic patterns through the synaptic interactions of several neurons. These bursts excite the motor neurons to protract the leg (swing it forward) and inhibit those responsible for retracting the leg. Pearson proposed a model to explain the generation of reciprocal activity of the flexor and extensor motor neuron.[Pearson78]

The rhythms of CPGs are affected by sensory neurons, interneurons, command neurons, and by hormones. Sensory neurons that respond to stress in the legs can influence the activity of the central pattern generator, slowing it down or inhibiting it entirely. An extreme stress on a leg may stop the gait. [Zill93]

The unit CPG hypothesis proposed by Grillner suggests versatile motor organization in which different component CPGs can be recombined in a variety of ways. [Grillner85] Varying the parameters in a CPG, such as the burst strength between individual pacemaker neurons, may permit the same CPG to control a variety of distinct gaits, and to cause transitions from one to another. [Collins92b] Nothof has confirmed that the different patterns of movements of a particular leg come from the same set of CPGs but with different coordinating interneurons.

Ethology and psychology of animal walking

Behavior includes all processes by which an animal senses the external world and the internal state of its body, and responds to what it perceives. [Manning92]

Reflexes tie sensory neurons to motor neurons

The simplest form of animal behavior may be a reflex, in which a fast, stereotyped response is triggered by a particular type of environmental stimulus. The defining characteristic of a reflex is that the intensity and duration is governed to a large extent by the stimulus. [Beer90b] Locusts and walking stick insects exhibit a tactile reflex to lift a leg above an object contacted during the swing phase. [Pearson84][Cruse91b] Reflexes typically involve only one or two synapses and essentially a direct connect from sensory neuron to motor neuron.

Depending on the activity status of the animal, the control system of the stick insect exhibits different reflex reactions. [Bässler89] For example, the reflex response to a tactile stimulus at the foot depends on whether the foot is in swing or stance. This mirrors Dante II’s `free foot` and `contact foot` behaviors which display different reactions to foot contact depending, upon which behavior is exhibited.

Taxes produce orientation responses

A taxis is an orientation response. Sound and smell are strong triggering senses; animals turn toward loud noises or the scent of food. Posture also depends on taxes; animals orient themselves with respect to gravity.

Swaying behaviors in grasshoppers (and also in vertebrates) adjust the flexion and extension of leg muscles to maintain a particular orientation to gravity. [Zill93]

Studying the posturing mechanisms in the walking stick insect, Cruse found decentralized leg control behaviors that explain the creature's ability to maintain its posture in irregular terrain. [Cruse89] During normal terrestrial walking, hexapod insects always maintain static equilibrium. [Graham85]

Patterned behaviors coordinate sequences of activity

Although a continuum of gait is possible, most insects exhibit a single, stereotyped gait during walking without respect to how fast or slow they are walking. For example, even at very slow speeds it is rare for a cockroach to depart from the tripod gait. [Delcomyn93]

Pattern generation, for example the stroking of fins by fish, is a behavior that innervates individual motor control behaviors and produces a coordinated result.

In studying the patterns of locusts walking on rough terrain, Pearson [Pearson78] found that locusts use rhythmic searching movements when the foot fails to contact the terrain at the end of the swing phase, and also prior to retraction, presumably to find a more suitable foothold.

During fast walking central pattern mechanisms for coordination predominate. During slow walking feedback from phasically-stimulated sense organs in the legs play the dominant role. A controller for slow walking may need different structures from one designed for fast walking. [Delcomyn93]

Behavior adapts

The adaptability and flexibility of gait is expressed in different ways, by different walking gaits (expressed in changes in the temporal and spatial relationships between certain legs), by different walking directions (changes in the coordination of the different joints of the leg) and by movements adapting to the irregularities of the ground. [Nothof90] Stabilized feedback control of a movement can elicit entrainment of the underlying motor pattern and further reinforce the pattern. [Grillner85] The more a behavior repeats, the more stable it becomes.

Pearson noted that locusts, unlike walking sticks, do not exhibit a follow-the-leader approach in foot placement, instead each leg individually searches for a foothold. [Pearson78] However, visual control of the forelegs and apparently intentional foothold selection has been observed.

Motivated behaviors

Behavioral choice, the ability to arbitrate among competing behavioral responses, may result from one or more neural mechanisms. The pattern generator of one behavior may directly suppress the pattern behavior of another behavior, or it may instead block access to needed neural motor circuitry. Another possibility it that the pattern generators for two behaviors actually share circuitry, making it impossible to exhibit both behaviors simultaneously.

Descending neural pathways activate individual CPGs to enable selective control of individual joints. Voluntary motor acts are initiated by will, either innate or learned, and result in movements or a step. [Grillner85]

Biology for robotic walking

A number of researchers have performed simulation studies of walking using neural models, or have tried to explain the neurological basis for walking by developing computational models of the nerve.

Cruse proposed that his model of the nervous system of the walking stick insect, which incorporates tactile reflexes and patterned behaviors, could be used to control a robot. [Cruse91a][Dean90] He has gone on to develop a simulation of walking motion with small obstacle crossing. [Cruse93]

Ayers has proposed implementation of an artificial lobster based on actual lobster neurology. [Ayers93] This system produces mainly the rhythms to coordinate the lobster's ten legs.

Beer and Chiel implemented a distributed neural network for controlling a simulated cockroach based on the neuroethology of insect locomotion. [Chiel89a][Beer92] The controller can generate a continuous range of statically-stable gaits. They built a heterogeneous artificial neural network in which individual nerve cells can excite or inhibit leg motions, or act as pacemakers to sequence legs and coordinate body motions. There are basic rhythmic movements produced by a CPG. Each leg is controlled by three motor neurons: stance and swing motor neurons (corresponding to flexors and extensors) determine the force (not position) with which the leg moves backward or forward; the foot motor neuron controls whether the foot is up or down. The foot motor neuron is normally active, and a command neuron excites the stance motor neuron which puts the foot down and pushes the leg back, the stance phase. Periodically this stance is inhibited by a burst from the pacemaker neuron which inhibits the foot and stance neurons and excites the swing neuron, the swing phase. The force applied by the stance motor neuron and the frequency of pacemaker bursts is determined by the excitation from the command neuron. Sensor neurons reinforce and modulate the stepping rhythm. A forward angle sensor inhibits the pacemaker neuron when the leg reaches all the way forward, ending the swing phase, and a backward angle sensor similarly initiates the swing phase. The backward angle sensor does not have a biological analog in the cockroach, in that it is a position sensor whereas cockroaches possess stress sensing neurons that modulate the gait as a result of leg loading. [Delcomyn93]

Six pacemaker neurons each inhibit their anterior, posterior and contralateral partner. This network of mutual inhibitions ensures that neighboring legs are not in the swing phase together. A similar arrangement is used by Ferrell [Ferrell95] and Donner. [Donner87] This inhibitory coupling produces a tripod gait at high speeds but at lower speeds is not sufficient to guarantee production of statically stable gaits. Alone it cannot produce metachronal waves seen in typical slow gaits—stepping patterns instead depend on the initial configuration of the legs.

Beer's insect produces metachronal waves instead by decreasing the burst frequency of the rearmost legs. Because of the inhibitory links to anterior legs, phase-locking occurs and the front and middle legs become entrained to the burst frequency of the rearmost legs, firing immediately afterwards and producing a metachronal wave. This entrainment breaks down for too slow a walk (or too fast a change in speed). The command neuron ensures stable conditions are maintained but as a result, the crawl gait is not possible.

To examine robustness, Chiel performed a lesion study of the simulated cockroach, in which some nerves were severed. It demonstrated the robustness of the nervous system, and showed that high-speed gaits, such as the *tripod* gait, are coordinated centrally while low-speed gaits, such as the *wave* gait, are not. [Chiel89b]

Lanthier has built an insect simulator similar to that of Beer, but differing in its neuron model—it uses a larger selection of neuron types and dendritic functions. [Lanthier95] Lanthier has achieved, in addition to the control of walking, map building and navigation with motivation-controlled behaviors.

Zheng developed a neural network that modified the gait of a biped climbing slopes. The network consists of reciprocally inhibited or excited neurons. [Zheng92] Two learning rules for speed of gait modification and minimum energy solution improve network performance during operation.

Walking robots aren't animals

Walking robots aren't animals, although they might usefully possess some of the same properties. Still, some things like the reliability of their motion and amenability to external monitoring and guidance force artificial solutions for robots.

Cruse, Beer, and others have built the gait controllers for walking robots by using models and concepts from animal neurology. Cliff has called this computational neurology and proposed the twofold purpose of creating artificial life and understanding natural systems. [Cliff91] Anderson proposes to take key concepts from behavior science and apply them to robotic science. [Anderson90]

What are some ideas that can be applied to walking robots? Multi-level architectures for walking can, whether they are hierarchies of modules, layers of agents, or something else bearing little resemblance to either the neurological or ethological models of insect walking both of which are massively interconnected. This elaborate, heterogeneous network suggests a possible construction for a behavior-based system (and is what I have constructed for Dante II).

Reflexes demonstrate that feedback mechanisms are selectively tied to sensory information. Sensed information is used to modulate some behavior but is not widely distributed throughout the nervous system. Paralleling this in software leads to a distributed, reactive system.

The neurons in this heterogeneous network all interact by excitory or inhibitory signals, but external influences can be applied to them by neurotransmitters which change their behavior. This suggests that behaviors interact by simple binary communication and that external influences adjust their internal properties.

The walking control system for animals is a combination of patterned behavior and reflexive coordination. Reflexes dominate slow, deliberate walking and keep animals safe in unsteady situations. This observation is borne out by the trend in research of robotic walking: analytical, planning-based solutions have given way to methods that emphasize reflexive action and fundamental safeguarding.

Animals do not necessarily make the best models for robotic walking. It is important to remember that the evolutionary pressures that led to animal walking have not been applied exclusively to creating an efficient (much less optimal) system; many other functions had an impact. [Delcomyn93] Robots need to do things that animals do not. Robots have different sorts of requirements for their performance, the tasks they undertake and the way in which they are operated.

In terms of performance, animals fall down, roll over, trip, and get up again. Until robots are as physically robust, their control systems must ensure that the robot does not damage itself. This is a different sort of evolutionary pressure than what an animal developed experienced.

Simple animals are still impossible to fully understand. For example, once Beer had produced in simulation just the basic pattern of walking, he found the extensive revisions needed to coordinate stopping, starting, turning with higher behaviors were extremely intricate. He ultimately found that much of the simulated nervous system was ad hoc, with some parts based on neurobiological data and other parts hand-made. He fine-tuned over 500 parameters by trial and error. [Beer92]

Animals produce their gait rhythm with central pattern generators. There are a number of reasons why this is problematic for robots. First, these systems are difficult to tune properly and verify. Tuning by entrainment offers the best hope, so a robot would need to learn to walk just as animal does. Some limited results show a promise but are far behind the capability of animals and existing walking robots. [Lewis92] Second, central pattern generators do not produce a consistent pattern for slow walking. Schöner showed mathematically that the rhythmic pattern of the CPG breaks down. [Schöner90] Beer found experimentally in his computational model and simulation that the slowest crawling gaits could not be produced.

For these reasons I chose not to employ central pattern generators but to let activation spread through an asynchronous behavior network.

SimPod, a simulated hexapod

To demonstrate that the method of controlling Dante II applies to walking robots in general, I created a computational simulation of a hexapod walking robot. Called SimPod, for simulated hexapod, this robot is capable of free gaits; its legs are not restricted to movement in frames. With SimPod I showed the capability of an extended behavior-based gait controller to perform a variety of gait patterns and switch among gaits on the fly. SimPod is shown in Figure 6-1, with six independent, three degree-of-freedom, orthogonal legs.

The ability to change among a variety of gait patterns—some more stable, some more rapid—is an useful capability that virtually every walking animal possesses, but Dante II lacks. Dante II presents a somewhat restricted form of walking since its legs always move in a fixed frame. Animals can selectively move individual legs to stabilize their stance or to move through rough terrain. [Pearson84] [Cruse89] This ability to produce free gaits is invaluable in extremely rough terrain.

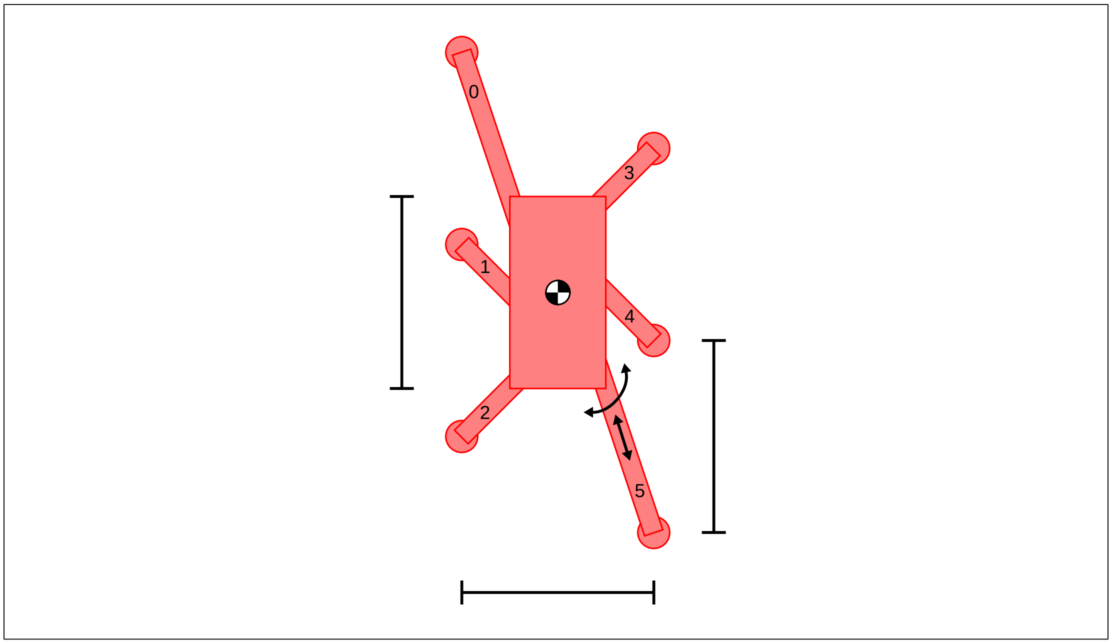

Figure 6-1: SimPod, geometry. The free-gait hexapod has 18 degrees-of-freedom and stride, tread, step height, and body length of equal dimension, for these tests one meter.

Simulations are notorious for restricting their domain such that success is inevitable and therefore meaningless. Many researchers have railed against the use of simulation and for situated agents, for example [Brooks91b]. In principle, I concur with these arguments and have experienced the impossibility of adequate simulation—a series of simulators for Ambler seemed realistic but never transferred well to reality. [Thomas90]

The purpose of this simulation, however, is not to ground this work in reality—that has been accomplished by Dante II. Instead, this simulation starts with the same real-time operating system and computing hardware used by Dante II's control, and increases the mechanism's complexity. One simplification was made for expedience; the walker does not turn in any of the tests. In terms of coordination and control, rotation is not substantially different from translation. (The added degrees-of-freedom do have an impact on planning, but that is not an issue here.)

The interface between behavior processes, and sensing and actuation verified by Dante II remain identical and mask the fact that feedback loops are closed in software rather than through actual legs. Before modifying the gait controller to operate SimPod, I verified it with Dante II kinematics and was able to walk indefinitely at a rate of about 2800 meters in 24 hours.

Simulation needs realistic terrain

To evaluate SimPod's ability to walk in rough terrain, some sort of realistic terrain simulation is necessary. As mentioned in **Walking in natural terrain**, the area observed by the Viking landers is rough and obstacle strewn—exactly the sort of environment where walking makes the most sense.

Viking lander imagery was used by Moore to develop a model of the rock size distribution per square meter. [Moore89] Moore's model gives the cumulative number of rocks per square meter n with radius r or larger as $n = \beta r^{\alpha}$, which is simply an exponential function as seen in Figure 6-2. For the Viking lander sites (such as Figure

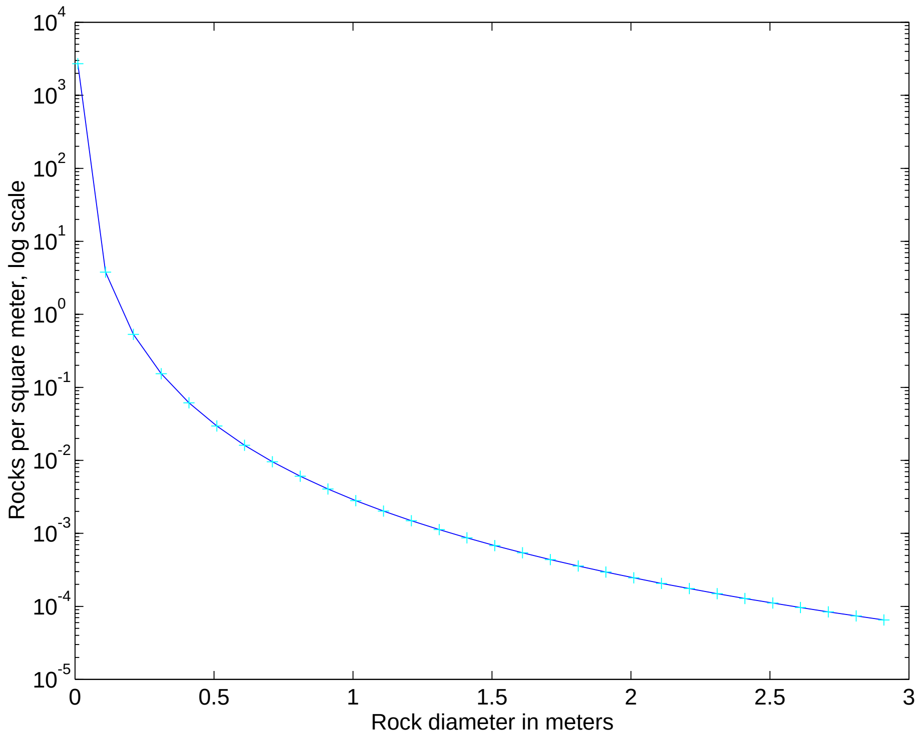

Figure 6-2: Frequency distribution of rock size per square meter near the Viking 2 Lander.

2-1) the coefficients, α = -2.66 and β = 0.013, accurately reflect the size distribution of rocks.

To create realistic terrain, I used Moore's model to determine the rocks per square meter for 10 meter by 10 meter patches. The model can be used to predict the frequency of sand grains, but this is impractical and probably not well grounded in the original empirical analysis. So, I started with a minimum 5 centimeter radius, and calculated the number of rocks in range intervals $r_{\min}$ to $r_{\max}$ with [6-1]. Each rock is then sized

$$n = \beta(r_{min}{}^{\alpha} - r_{max}{}^{\alpha}) \qquad [6\text{-}1]$$

randomly within its range interval, located randomly in the terrain patch, and sunk into the terrain to a random depth (within one quarter radius of its center). This method of generating realistic terrain was used for Ambler, [Thomas90], and recently by NASA to prepare for the robotic exploration of Mars. [Mathies95]

I generated a number of terrain examples and discarded those that did not seem to pose an interesting challenge. I chose three terrains, shown in Figure 6-3, that presented substantial obstacles and some smaller rocks for the hexapod to attempt to walk over.

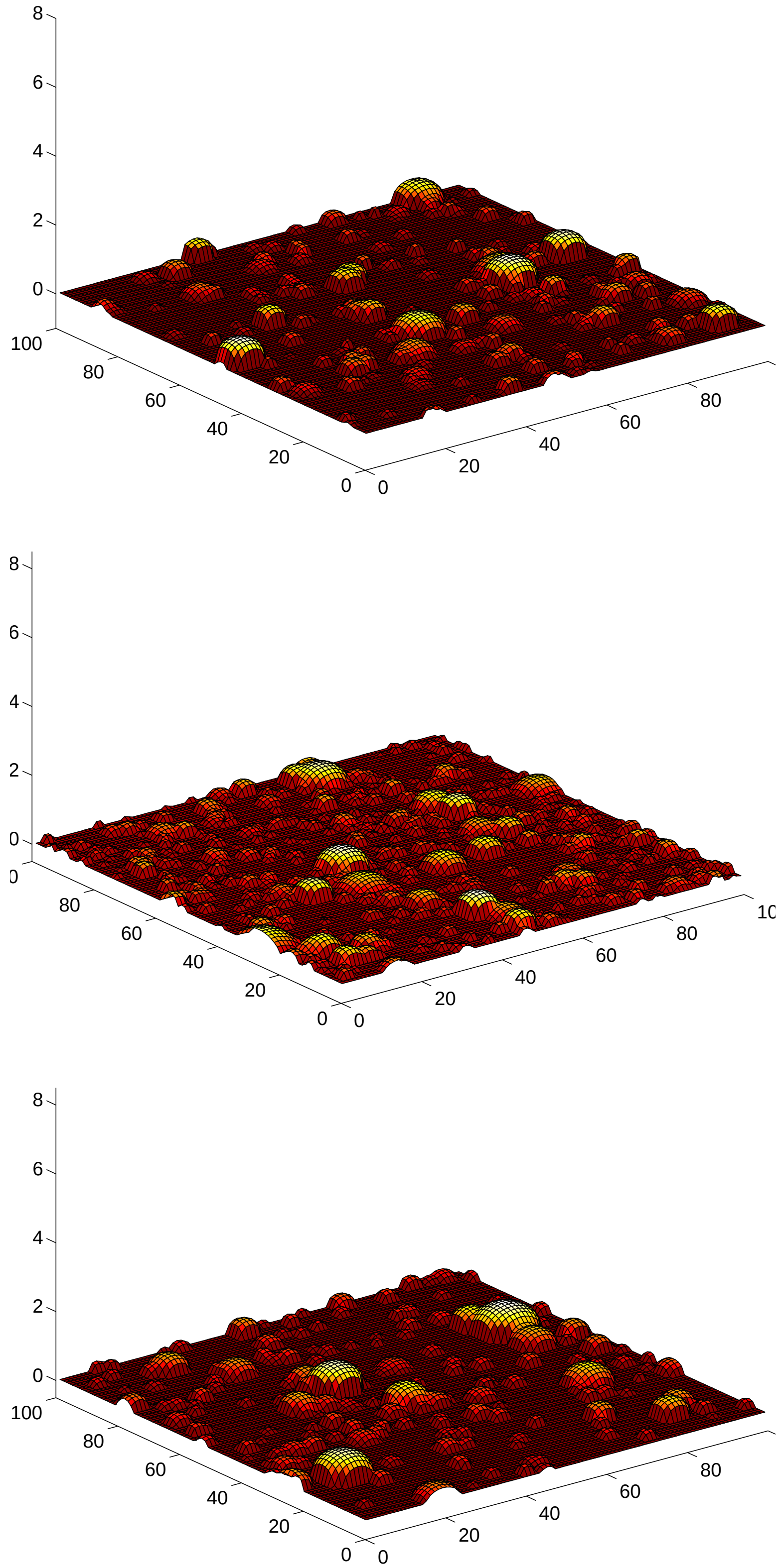

Figure 6-3: Terrain elevation maps generated with Moore's model of rock distributions.

Behavior-based control generalizes to multiple gaits

SimPod has eighteen total degrees-of-freedom (versus ten for Dante II) and the possibility of performing a variety of different gaits. It can independently move each of its three degrees-of-freedom legs. To control the added motions additional behavior control processes are needed. Six `swing leg` behaviors move individual legs forward and back. The vertical motion of each leg is still controlled with `contact leg` and `free leg` behaviors, although the number of each is reduced to six.

A `swing leg` behavior produces an independent swing phase for each leg. It sends an exhibit signal to the `free foot` behavior of its associated leg and monitors the external forces on the leg until it is free of the terrain and able to swing forward. The `swing leg` behavior then generates an appropriate servo reference to advance the leg and also sends an exhibit signal to the `move body` behavior so that it can advance concurrently.

While a leg recovers (swings) and the body advances the `swing leg` behavior inhibits the `move legs` behavior. This is to ensure that additional legs do enter the swing phase. This interaction represents a departure from the cycle of exhibit links used for Dante II. For frame-walking gaits, body motion strictly precedes leg placement (exhibition of the `contact foot` behavior), but for more general gaits, body motion and the support phase of some legs is concurrent with the swing phase of other legs. The inhibition of the move legs behavior is necessary to ensure that swing phase is complete (that all the recovering legs have reestablished ground contact) and it is safe to swing the next group of legs. This interaction is diagramed in Figure 6-4.

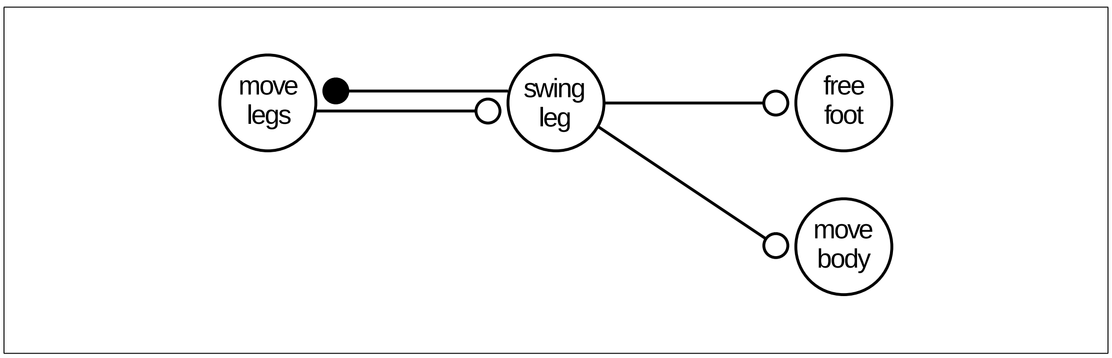

Figure 6-4: The swing leg behavior for each leg is exhibited by the move legs behavior. It exhibits free foot for its associated leg (free foot in turn inhibits contact foot for that leg) and waits for the leg to break contact with the terrain. When the leg is free, the swing leg behavior commands the leg to recover forward and also sends an exhibit signal to the move body behavior to allow concurrent body advance.

With a robot capable of non-frame gaits, a means of ensuring stable support is needed because it is possible to raise enough legs to leave the center-of-gravity unsupported and cause a tip-over. Simpod can tip over by, for example, raising all the legs on its left side. This means that the center-of-gravity must always be enclosed by a polygon of supporting legs—an adequate group of legs must remain on the ground to maintain static equilibrium. This can be achieved by keeping the adjacent neighbors of each free leg on the ground. A `support` behavior does just this: if a leg is free, the `support` behavior inhibits `free foot` and exhibits `contact foot` for its adjacent neighbors. Regardless of the gait—wave, tetrapod, tripod—the robot cannot pick up enough legs to leave its center-of-gravity without support. The single `support` performs a similar function to six coordinating behaviors used by both Beer and Ferrel [Beer90b] [Ferrell93] More sophisticated selection of minimum supporting legs is possible, for example taking into account inertial effects and the effective of non-zero diameter feet but this simple algorithm has proven adequate.

The `move legs` behavior is a replacement for the `raise legs` behavior of Dante II. It is the source of SimPod's ability to produce a broad spectrum of gait patterns and can generates a number of gait patterns involving individual or groups of legs, and also a free gait in which the most limiting (extended) leg is moved. `Move legs` stores in internal state which gait pattern it is applying and the last leg(s) moved. The gait pattern is parameterized, so that it can be externally modified either by an operator or by a separate planning process.

The `move legs` encodes internally various stable gait patterns. More patterns can be added with a simple state encoding. The move legs behavior also has the critical capability to generate aperiodic, free gaits to smooth the transition among gait patterns. When legs have reached their kinematic limit, they are advanced, regardless of the current gait pattern by exhibiting the appropriate `swing leg` behavior. This allows SimPod to change gaits on-the-fly but still resequence legs if they are at the wrong point in their *leg cycle*. Also, by storing the last leg or legs recovered, the `move legs` behavior can detect and eliminate repeated recovery of the same leg.

A `move body` replaces `move frame` but acts in a similar manner, keeping active an intention to drive the body to a desired position. It displays summation somewhat like a neuron in that it is exhibited by one, two, or three `swing leg` behaviors, depending upon the particular gait being performed. The greater the number of recovering legs, the greater the frame advance.

Multiple hexapod gaits are enabled

For a hexapod gait is a continuous function of stepping frequency. Along that continuum certain gaits predominate in the natural world. Beginning with the wave gait, in which one leg recovers at a time, these gaits are characterized by having legs recover together in phase or one-half cycle out of phase. For the SimPod I have encoded the patterns of a number of the most common gaits.

Figure 6-5 shows an alternating wave gait in which a metachronal wave propagates from the rear. This crawling gait recovers a single leg at a time (for a duty factor of 5/6) so it is maximally stable. It is best suited to rough terrain and there is some evidence that animals, locusts for example, employ it for that purpose. [Pearson84]

The centipede *Scolopendra* moves its legs in sequence from front to rear (an alternating metachronal wave) but the centipede *Scutigera*, which has long legs, moves them in the reverse sequence from rear to front to avoid conflicts between the legs as they draw close or cross. [Alexander92] Bares has also developed several arguments for the anti-metachronal wave, based on reuse of the vacated anterior footprint.[Bares91] The principle advantage is that the leading legs probe new terrain, to find footfalls and test support and then the trailing legs step, follow-the-leader, into footprints vacated by leading leg. [Özgüner84] Without any increase in complexity, the controller for the

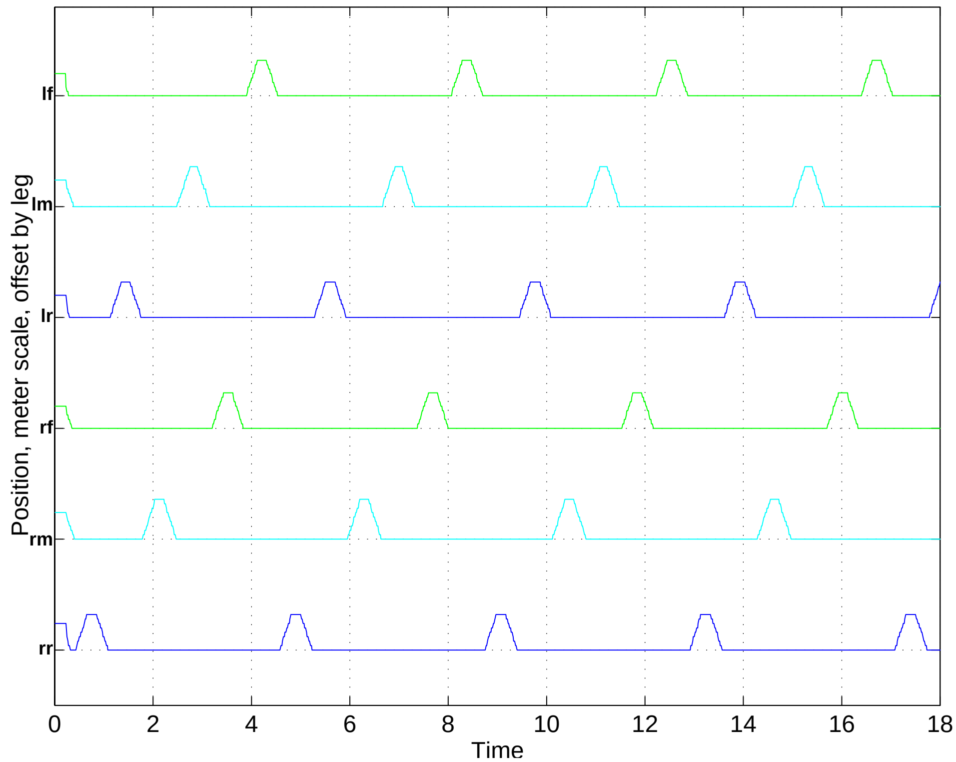

Figure 6-5: Metachronal wave gait. Protractions alternate from the rear. The most stable gait for a hexapod.

hexapod can also produce stepping waves that propagate from the front, as seen in Figure 6-6.

The tetrapod gait, named because four legs support the hexapod, has two legs simultaneously recovering. Shown in Figure 6-7, it has a duty cycle of 2/3. The tetrapod of the hexapod should not be confused with the alternating tetrapod of an octopod, in which four legs recover simultaneously—in both cases four legs provide support. This gait is sometimes called a ripple gait because a ripple of leg recoveries travels the body. This is particularly apparent with multipeds.

The tripod gait, shown in Figure 6-8, is the highest speed statically-stable gait for a hexapod. It has a duty cycle of 1/2, meaning that each leg is supporting half the time and recovering half the time. For a hexapod, the faster gaits in which only two of the six legs support are possible, although they are not quasi-static.

SimPod switches gaits on-the-fly

Animals apply different gaits to different situations. Some gaits are slow and stable, like the crawling gait employed by turtles, while others are faster but less stable, like the tripod gait preferred by cockroaches. The behavior-based gait controller only needs to produce an alternating tetrapod gait for Dante II, but as I describe here, it can be enhanced with several additional behavior processes so that it can produce a variety of gaits.

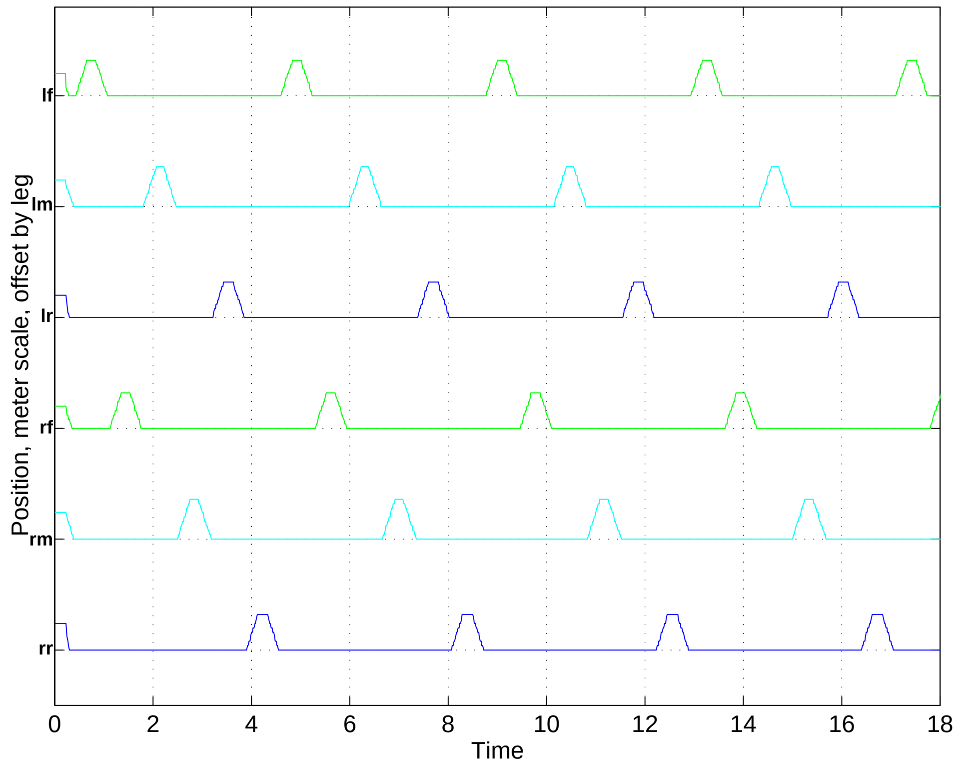

Figure 6-6: Alternating wave gait propagating from front to rear.

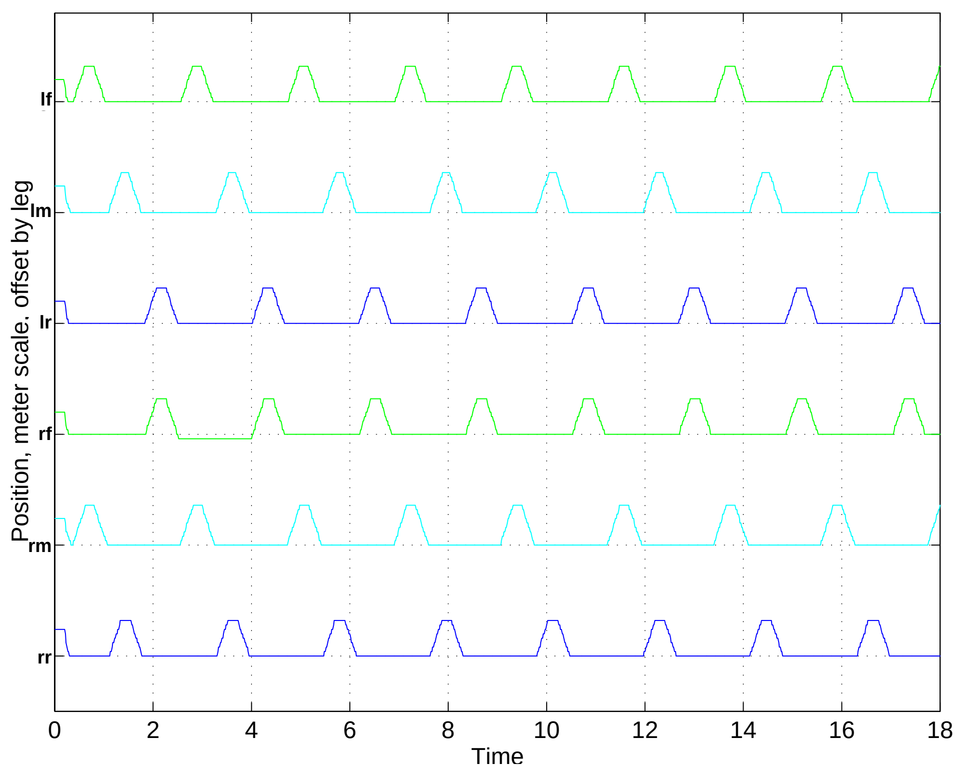

Figure 6-7: Tetrapod (or ripple) gait: four legs support while pairs recover. The ripples can propagate from either the front or rear.

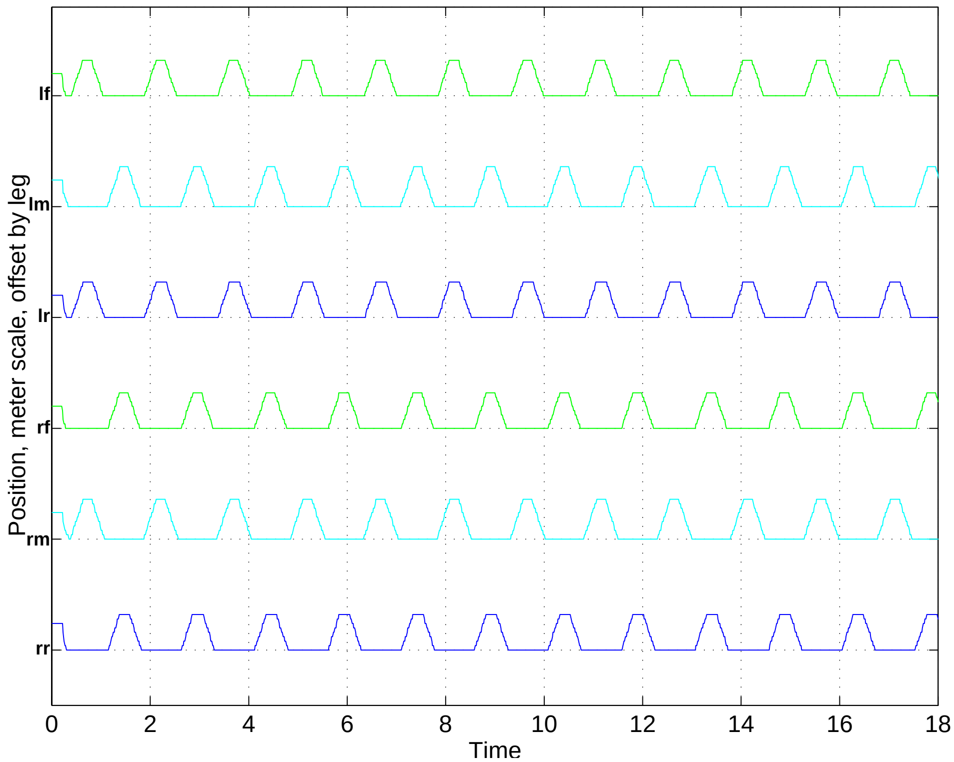

Figure 6-8: Tripod gait: three legs support while three recover. The fastest statically stable gait for a hexapod.

Why change gait? Animals change gait for several reasons, to change speed, to improve stability, or to adapt to terrain. They select a gait to travel as economically as possible, and typically avoid speeds at the transition. [Alexander92]

Gait switching has been shown, to a limited extent, in a few existing systems. Almost always a walking robot must stop, place all its legs on the ground, possibly shuffle them to new positions, and then proceed in the new gait pattern. This work is distinguished by the ability to switch gait without preparing in advance, without stopping, and without unnecessary leg resequencing.

Some robots (for example in [Ferrell95]) have been able to shift gait pattern by changing the gait frequency defined by Wilson. [Wilson66] The robot may be able to walk continuously but at changes in gait frequency, half-steps can occur. Changing gait pattern in this manner neither guarantees stability, indeed Wilson indicates such transitions may be unstable, nor does it allow arbitrary change of pattern. For example, a change from tripod to wave is not possible. Neither is it possible to change from front-to rear-propagated gaits.

Kumar analyzed gait transitions, specifically between periodic gaits, and identified a set of inequalities relating duty factor and the relative phasing of the legs before and after the transition to decide which transitions are possible. [Kumar89a] Such a method requires derivation of satisfactory intermediate duty factors and phase differences, presumably by search. Stable transitions need not exist and indeed, because it involves uniform adjustment of gait parameters, any intermediate stance may be unstable. Kumar suggests that to ensure stability and adequate time to reduce speed, the gait optimization must occur several gait cycles in advance of execution. I show here that this planned optimization of stability is unnecessary if spontaneous free gait steps can be inserted within the pattern to adjust kinematically-limited legs.

A free gait is an unrestricted sequence of steps in which any leg can move at any time. The guiding concern is stability throughout the sequence. Free gaits enable rock-hopping and the maneuvering required to crawl through dense obstacle fields. Free gaits, in the form of added aperiodic steps, can smooth the transition from one periodic gait to another; more than simple timing changes, switching gaits may require a spontaneous free gait to correct leg motion limits. While switching gaits the robot must maintain stable support, produce a free gait to unwedge legs that are at their limit, and avoid recovering the same leg twice in a row.

The changes in gait presented as examples in Figure 6-9 and Figure 6-10 were imposed by the operator; the internal storage of the current gait by the `move legs` behavior is parameterized so that it can be changed by the operator.

In Figure 6-9, the hexapod initially walks with a metachronal wave gait, at minute 9 it switches to a tetrapod gait, and at minute 19 switches to a tripod gait. At minute 25 the gait slows into a wave. The supporting legs have adjusted to the relative phasing of the tripod so the left middle and then right front (which were previously moving in conjunction with the right rear) recover aperiodically to adjust their relative phase. Later at minute 29, the left front leg reaches the limit of its support stroke before occurring in the gait sequence and must recover out of order to correct phasing. At this time the metachronal wave is established. Transitions to tetrapod (minute 35), an anti-metachronal wave (minute 45) and tripod (minute 53) occur without interruption in periodicity. The elapsed real-time is 60 minutes and the distance traveled is 30 meters.

Figure 6-10 evidences both spontaneous free gait to correct relative leg phasing and suppression of double recoveries. SimPod initially walks with an alternating wave propagated from the rear. At minute 10, the operator switches the gait to an anti-metachronal tetrapod. The first recovering pair is the left front and right middle legs, however the right middle leg has just recovered and has begun the support phase. Repeated recovery of the middle leg, which will land it back in its current position, is suppressed and the left front leg recovers alone, setting the gait into proper accord.

Similarly at minute 18, the gait speeds up to a tripod and double recovery by both the left front and right middle legs is avoided. SimPod slows to a wave at minute 22, restrains double-recovery by the left front leg, and then similar to Figure 6-9 recovers legs aperiodically to avoid kinematic limits. Leg limiting occurs as the duty cycle increases (the robot slows) and legs increase their support stroke. The gait changes through tetrapod (minute 42), wave (minute 49), and tetrapod (minute 55), and double-recoveries are restrained throughout. The distance traveled is about 33 meters in 60 minutes.

Proprioceptive walking in rough terrain by SimPod

Like Dante II, SimPod is able to walk proprioceptively through rough terrain, which is to say it uses only internally-sensed positions and forces.

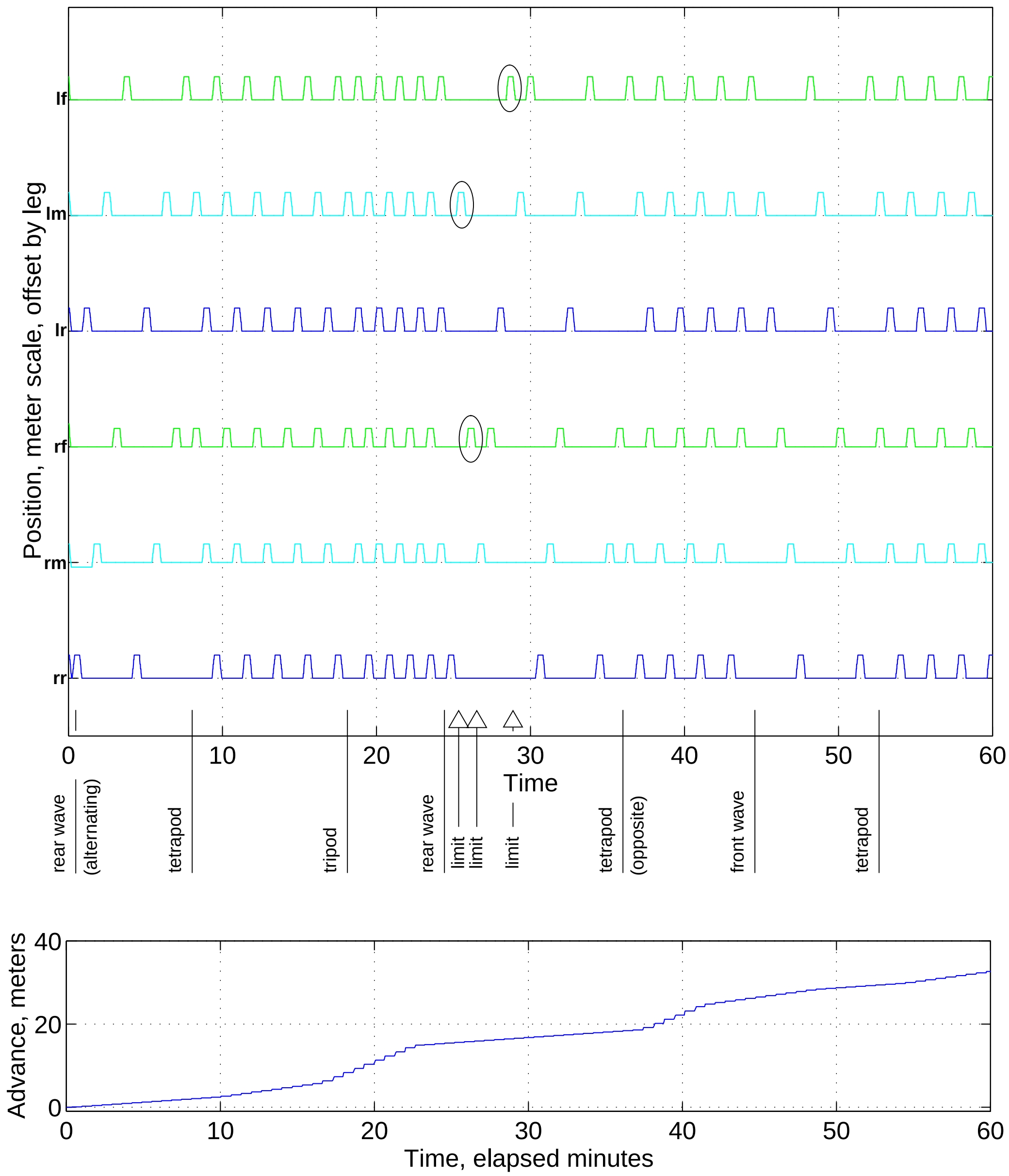

Figure 6-9: SimPod switching gaits (and recovering limiting legs) on flat terrain (above) and advance relative to time (below). In 60 minutes of actual run-time, the SimPod advances 30 meters.

In the first sample terrain, SimPod walks with a crawling wave gait, shown in Figure 6-11. The left front leg begins the walk already up on a rock. At minute 1 the right middle leg raises up, protracts, and lowers slightly onto a rock. As legs encounter rocks while swinging forward, they raise up until they clear the rock, and then continue to protract. This behavior is exhibited very clearly by the left rear leg at minute 8, the right front leg at minute 11, and the left front leg at minute 12. Large rocks, almost 0.5 meters in height, are encountered by the left middle leg at minutes 15 and 29.

This elevation reflex is the same as demonstrated by Dante II, for example in Figure 5-19 at minute 119. Each leg raises to a nominal height, swings forward, and sets down on the terrain. If an obstacle is encountered during the swing phase the leg raises further

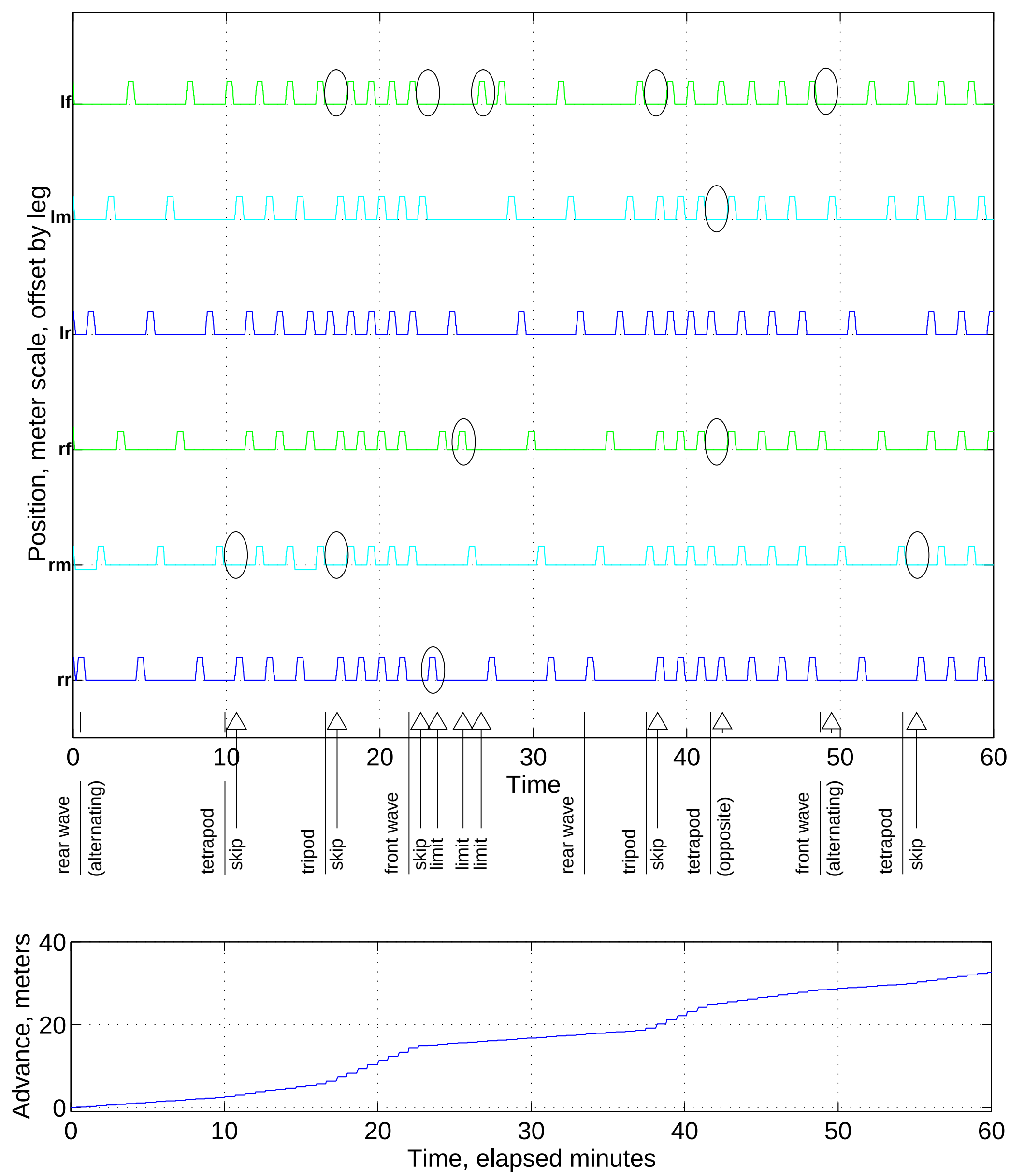

Figure 6-10: Hexapod switching gaits (and skipping repeated recovery) on flat terrain. Changes in gait pattern are initiated by an operative.

until it is free. Figure 6-12 shows the placement of feet in this first sample terrain, depicted in its entirely in Figure 6-3, top.

The contour of the terrain repeats in the lifting pattern of ipsilateral leg groups; obstacles first encountered by the leading leg are later bumped into by the middle and then rear legs. Locusts walk like this, discovering terrain with each leg independently [Pearson84], but walking stick insects do not [Dean90], they instead use the position of the leading leg to determine the behavior of the adjacent trailing legs.

The second terrain gait is shown in Figure 6-13. The initial foot placements for the left front and middle legs penetrate an object. Their behavior on recovery (minute 3 for the left middle leg and minute 4 for the left front leg) illustrates the effect of continuous

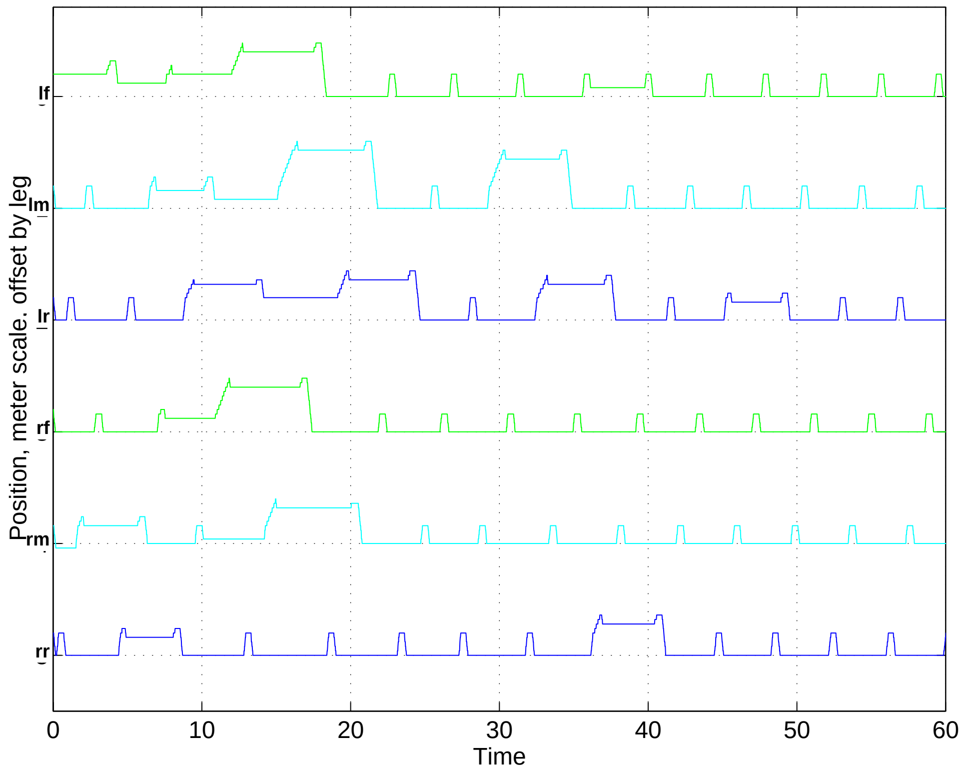

Figure 6-11: Vertical leg position while traversing first sample terrain from Figure 6-3, top.

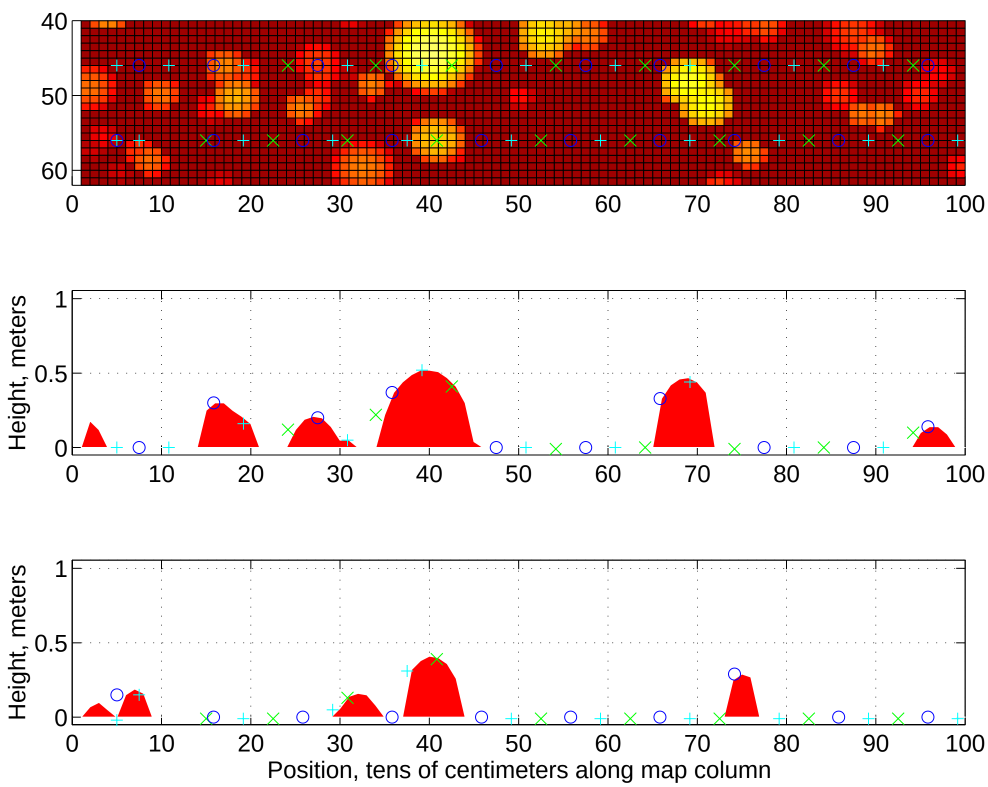

Figure 6-12: Foot placements in first sample terrain. Plan view (top) with lighter shading indicating higher elevation. Side views of left (middle) and right (bottom) legs: x = front, + = middle, and o = rear leg.

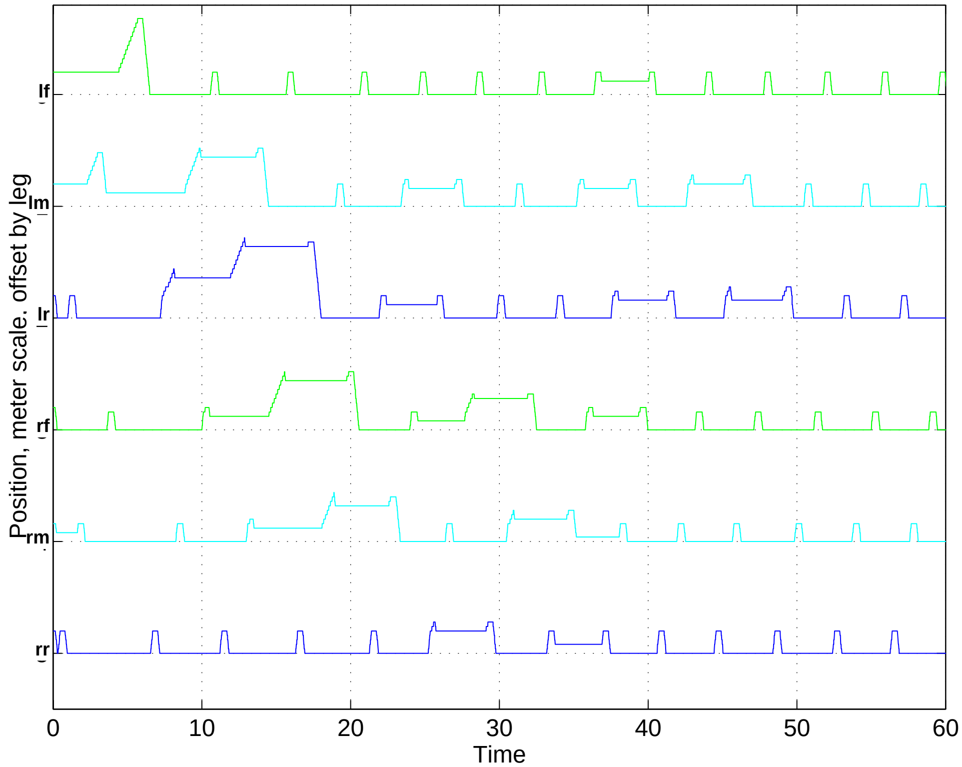

Figure 6-13: Vertical leg position in second terrain (Figure 6-3, middle). As a leg contacts a rock, as the left rear leg does at minute 8, it continues to raise, above the nominal step height, until it is free of the obstacle.

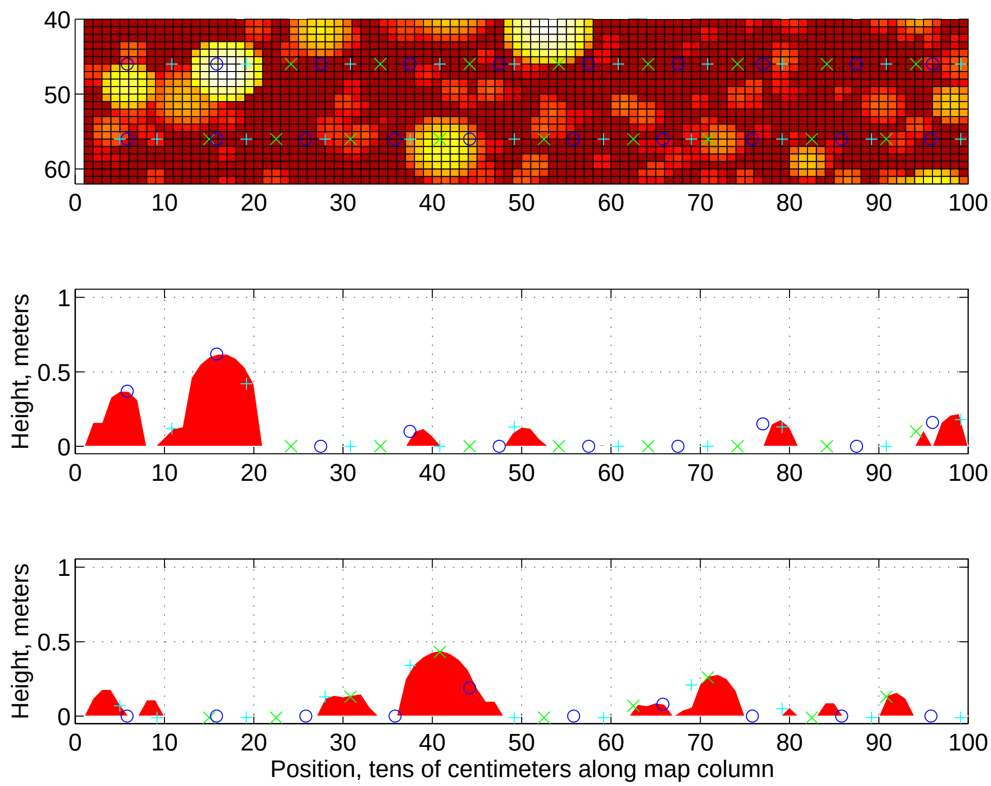

Figure 6-14: Foot placements in second terrain in plan (top) and side (middle, bottom) views.

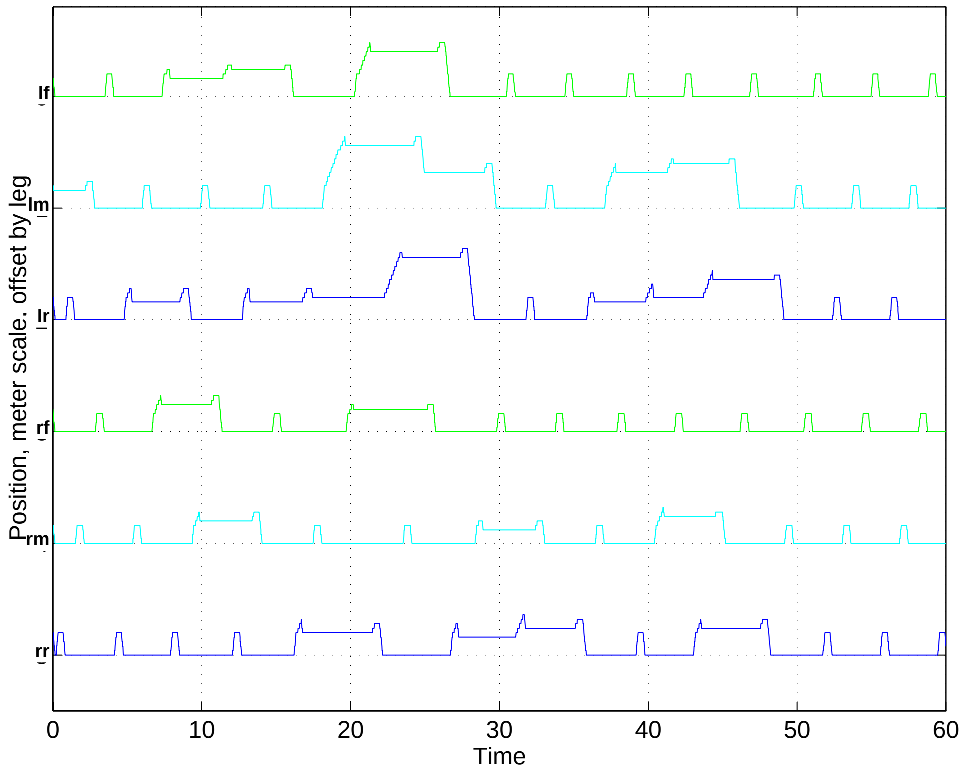

Figure 6-15: Vertical leg position in third sample terrain (Figure 6-3, bottom).

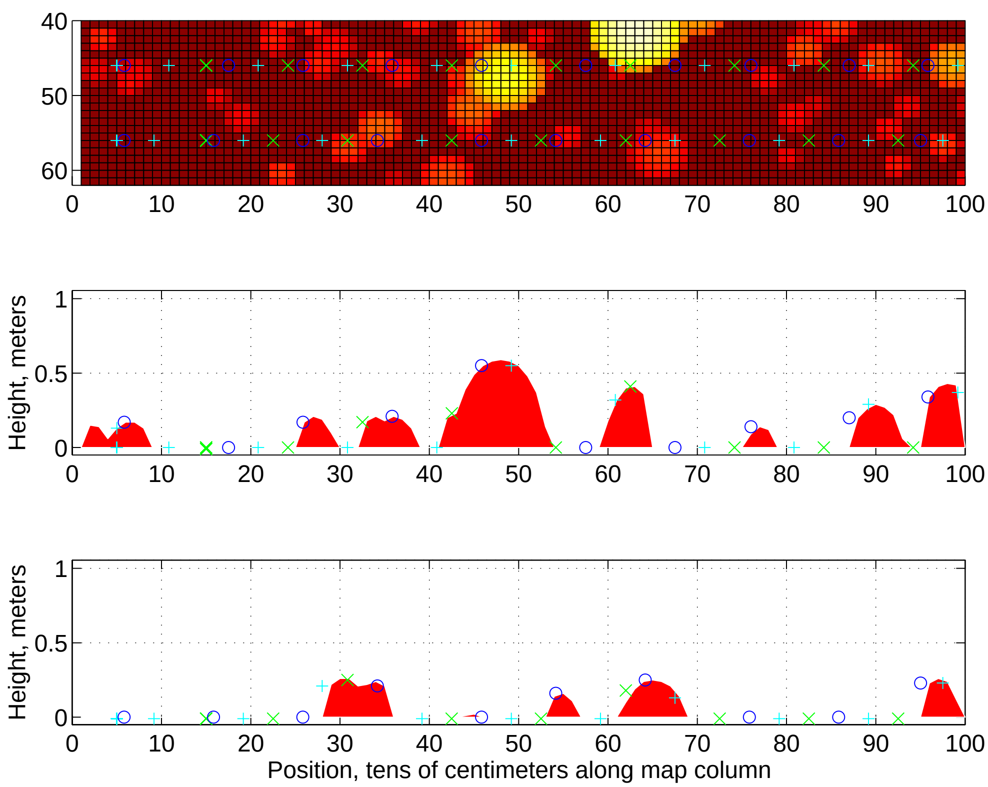

Figure 6-16: Foot placements in third terrain in plan (top) and side (middle, bottom) views.

contact while the leg is raising, as when the leg is deep in mud or scraping up a rock face. The leg continues to raise up until it is free of the terrain. The body then advances and the leg places on clear terrain. The specific foot placements appear in Figure 6-14; at the top is a top view of the footfalls, the periodic nature and uniform stride are apparent once the gait is established. The middle and bottom portions of Figure 6-14 are side views of the terrain encountered by the left and right legs, respectively.

Figure 6-15 presents a third example of proprioceptive walking. Corresponding foot placements appear in Figure 6-16.

Switching gait in rough terrain

While walking through rough terrain, it is sensible to choose a single stable gait; for hexapods a crawling wave gait is appropriate. There may be instances where switching gaits is called for in rough terrain, perhaps to cross a ditch or maybe to execute a spin maneuver. Figure 6-17 illustrates that SimPod can switch between multiple gaits and adapt to rough terrain. SimPod changes gaits from wave gait to tetrapod (minute 9) to tripod (minute 18) and back to wave (minute 25). Double-recoveries are eliminated at each transition. Limiting legs are stepped into proper relative phase as the wave gait passes from rough to smooth terrain. SimPod is slowed occasionally as legs contact obstacles and raise up, but travels 35 meters in 60 minutes of elapsed real-time (0.58 m/min).

Limitation to statically-stable walking robots

What are the limits of this generalization of behavior-based gait control to different walking robots? One limitation, which defines the scope of this thesis, is that the walking robot is must be statically stable.

An effect of this assumption is that the gait controller does not compensate for time-dependent effects (like the inertia experienced during dynamic gaits). For example, when running it is not usually possible to halt body advance when a leg collides with the terrain. It may be possible to respond with an appropriate reflex but this gait controller does not guarantee timeliness. That is an area for future development. In controlling dynamic hopping robots, Raibert was able to reduce control to three independent control laws. This is tantalizingly close to three independent behaviors, and the solution may simply be faster computer but it is more likely the case that development is needed.

The method of behavior-based gait control developed in this thesis has been demonstrated for a frame-walking octopod and a general hexapod. The coordination of gait is independent of leg number implying that this method applies to the statically-stable gaits of quadrupeds, quintupeds, hexapods, and higher-order multipeds.

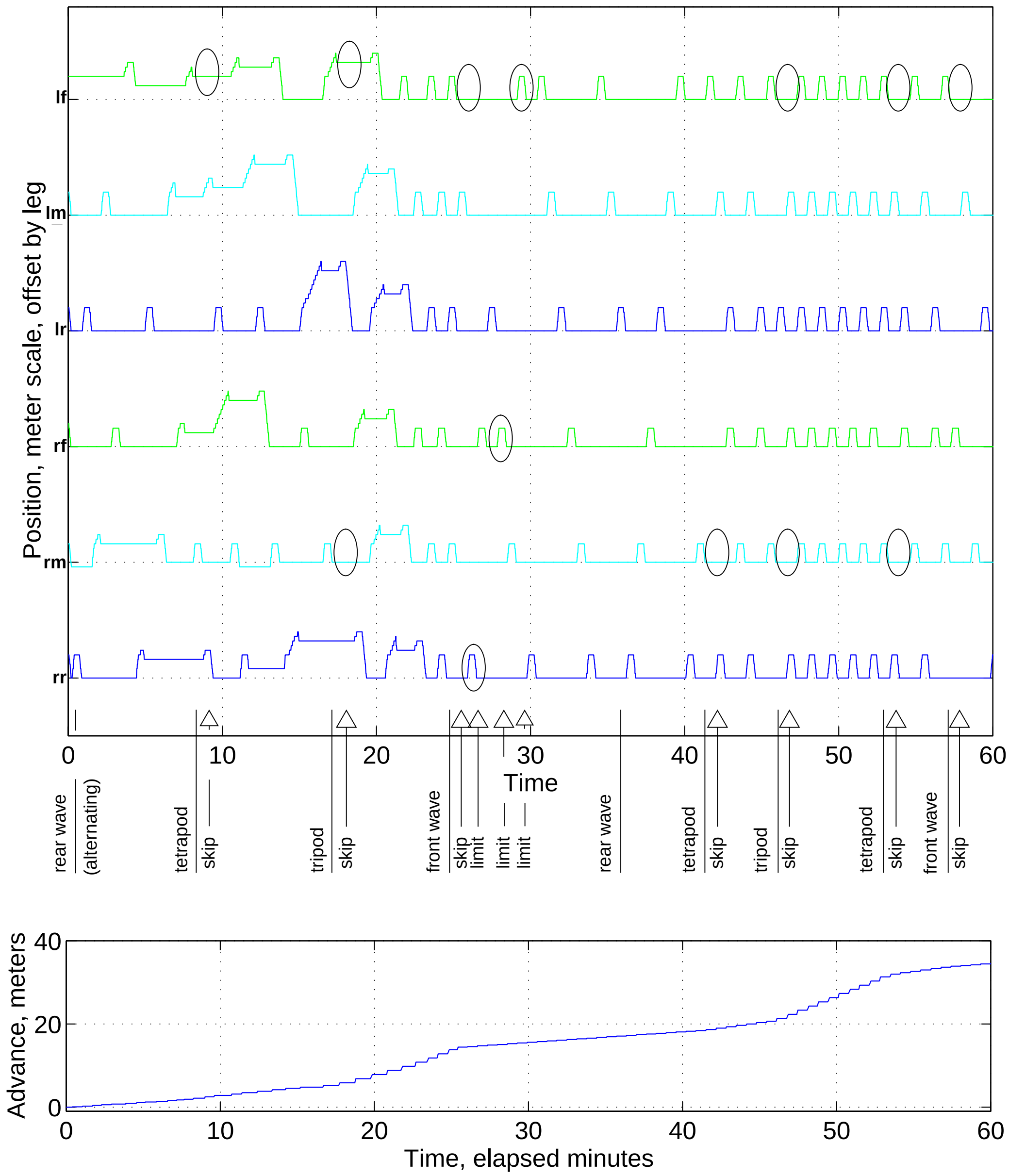

Figure 6-17: Hexapod switching gaits (and skipping repeated recovery) on flat terrain

Summary

- Animals provide useful insights into how gait might be controlled in a robot. They have a massively distributed heterogeneous system of neurons. Neurons are specialized into various functions and form decentralized reflexes. Rhythmic patterns are generated centrally and work in conjunction with reflexive reactions to produce walking.
- Robots can employ some of the constructions used in animals, but do have some important differences. They can't fall down as often, they must be more energy efficient, and have much more limited computing and sensor processing capability.
- The behavior-based gait controller developed for Dante II scales to control a more complex, eighteen degree-of-freedom hexapod, called SimPod. SimPod can walk blindly through natural terrain cluttered with obstacles half its own dimension. It reacts to contact with obstacles, stepping over them while adjusting the periodicity of its gait.
- SimPod can exhibit multiple gait patterns, including crawling waves, tetrapods and tripods. It can switch among these gaits on-the-fly as commanded by an operator or external planner, maintaining stability throughout. It spontaneously generates free, aperiodic gaits to correct leg sequencing and avoid kinematic limits. This is a novel capability for walking robots.

Chapter 7

Integrating planning and reacting

In **Integrating planning and reacting** I discuss the need for both planning and reaction in controlling a walking robot. The idea of integrating planning and reacting is not a new one. Indeed, there is substantial psychological and neurological evidence that animals do just this; they enact intentional behaviors as the result of cognition, albeit simple, and in a thoroughly integrated physiological system also display reflexive actions. There seems to be growing consensus that planning and reacting can be applied to different aspects of robot control in a complementary manner. I examine some existing hybrid architectures and develop specializations for the control of a walking robot.

Behaviors provide safeguarding reflexes and produce the gait pattern. I describe how they are parameterized and how plans for each aspect are made independently. Instead of planning a sequence of motions, SimPod avoids overspecifying actions and still improves performance by planning aspects of a preferred gait. I then present an implementation of deliberative planning that guides walking behavior allowing SimPod to walk over obstacles, minimizing contact and disturbance. All the reactive capabilities remain intact; in fact, if plans are inadequate or unavailable, the robot still walks stably, safeguarded by its fundamental behaviors.

Then, I present results of an experiment in which SimPod walks across terrain, this time guided by independent planners which advise several aspects of its performance. SimPod avoids terrain collisions and its gait becomes more productive, demonstrating the benefit of plan guidance.

Planning and reacting

A robot built of pure deliberative reasoning iterates a sense-plan-act cycle to produce motion. It perceives the surrounding terrain and instantiates some abstract representation. It also represents its own state and intentions. It decomposes strategic goals, for example, the path to walk along, into simpler goals. This recurs until the goals and sensed information are at a similar degree of abstraction and a mapping from current state to goal state is found among the available actions. This method, often involving search in an appropriate configuration space, can potentially identify the optimal sequence of motions to reach the goal. The plan is a complete prescription. The robot then begins to perform the actions. It monitors its actions, and eventually either reaches the goal or discovers that it can no longer adhere to the plan. The plan is susceptible to imprecision in sensing, modeling and control. Its failure arises from these errors and from unpredicted changes in the state of the world. Whether the plan succeeds or fails, the robot proceeds by reiterating the sense-plan-act cycle from its current state.

At the other end of the continuum, a purely reactive robot walks by its sense of touch and balance. It can stand stably by monitoring its roll and pitch and adjusting its legs to balance. It can pace in place by lifting or lowering sets of legs, such that a sufficient set is always on the ground. It walks, exhibiting a nominal gait, by following a prespecified pattern. The pattern may be based upon a neurological model and produced by a central pattern generator or it may be established as a collection of reflexes, each of which reacts to events sensed directly. The robot may not have a particular destination as its goal; that probably requires more sensing than touch and balance, but perhaps not much. The goal is better expressed in terms of what the robot can sense: a particular state. The reflexes are thus devised to maintain or immediately return to that goal state. For example, if a leg is moving and it contacts something (not a desired state) the leg raises up. The desired effect is to break contact but the net result is that the leg steps over the obstacle. A carefully devised set of behaviors can enable the robot to walk along, robust to the abuses of the terrain. Where it ends up is largely dependent upon the obstacles that it encounters.

Consider a walking robot that combines both approaches. It has a nominal gait, a sort of blank template, and a set of essential reflexes that keep it from colliding with obstacles or overturning itself. It has an inherent ability to walk blindly. Concurrently, the robot perceives and models the world. It only considers big issues, ignoring those known to be surmountable by reflexes alone. The space in which it plans is more abstract, simpler, making planning itself less complicated. If a substantial obstacle or impossible terrain is detected, the robot devises a plan that avoids the region but still forwards the long-term goals. This approach does not resort to prescribing actions, instead the plan is expressed in terms of the characteristics of the nominal gait. The parameters that fill out the blank template (for example, the step height, the ground clearance or turn amount) are revised and the robot changes its behavior accordingly. What if the revised parameters are late or incorrect? It doesn't matter—the reflexes, continually reacting to unexpected events like slips and bumps, keep the robot out of trouble. With a planner that considers future actions and their consequences to modify behavior, the net result is that robots actions are locally robust but also follow the global goals.

Planning provides foresight but requires modeling

Planning involves predictions that can provide guidance to the robot by foreseeing the consequences of its actions. Not all variables that affect the future course of action can be directly inferred from sensor input. So, to avoid wandering around blindly, the robot perceives the surrounding terrain and builds a representation from which it can predict passable routes. Unguided exploration can be blocked in apparent dead-ends that with slight adjustment to the gait are quite passable. Avoiding entrapment, either from an unproductive gait or from impassible terrain, is usually desirable. Foresight, prediction, and anticipated actions are necessary for productive locomotion. Some situations must be prepared for in advance, ditch crossing is one example.

Gait planning is formulated as deliberation in the space of free gaits. It arbitrates among competing goals and selects the gait that is the best balance of risk, energy and time. Planning is useful if it correctly predicts the effect of candidate actions so they can be wisely chosen.

Reacting simplifies sensing and acting

There are two principle difficulties with planning. The first comes from imprecise sensing, modeling, and control and leads to poor predictions and the second comes from unexpected (and unpredictable) events—typically events that occur in a period less than the sensing time. Even slow moving statically-stable robots require fast reactions to maintain equilibrium and resist sudden disturbances. Animals in rapid motion over terrain demonstrate the great efficiency of biological systems in solving the problems of legged locomotion. These biological systems provide evidence for decentralization of control and direct sense-act reflexes.

Reactive architectures address this problem by continuously relating sensation directly to action. These sense-act mappings establish planned reactions to expected, but unpredictable, events. Brooks [Brooks89] showed that walking could be executed reactively in this manner.

Biological systems also provide evidence for simple sense-act reflexes and decentralized control in walking. Working from a neurological basis, these systems are constructed of inhibitory and excitatory links between neurons to create reflexes and with central pattern generators to sequence fixed patterns of action. Beer [Beer92] built a system based on such a neurological model and has demonstrated robust walking.

Integrating both planning and reacting

Research into the control of walking locomotion seems, in recent years, to have divided almost completely into two paradigms. In one, walking is a mechanical activity that can be analytically modeled, accurately planned and strictly controlled. In the other model of walking it is an emergent property, either of muscles and neurons, behaviors and reflexes or some other independent control processes that interact to form useful patterns.

The idea that integrating planning and reacting is a preferred solution has recently gained wide acceptance in some applications of artificial intelligence, mobile robotics being one. I have developed and demonstrated this as it applied to gait control for walking robots.

The difference between the first two approaches may lie only in how the robot represents information; in an abstract data structure or inherent in its predetermined reactions.[Gat93] In the deliberative approach, the robot represents the relevant world information and then identifies short-term actions that advance long-term goals. The reactive approach does not plan explicitly. It instead maps stimuli directly to actions and embodies desired walking characteristics implicitly.

There is a middle ground that says that intelligent behavior, or as the domain I am concerned with here, walking behavior, is a combination of all approaches. I will subscribe to that opinion for scientific and practical reasons. Scientifically, an approach that combines deliberative reasoning and behavior-based reacting provides the most comprehensive explanation of skillful robust walking that exists, namely that of animals. Practically, it offers a method of controlling a walking robot that is both robust to disturbances during walking but also to high-level direction, guidance and optimization of performance.

A walking robot needs to both plan and react. Attempts to apply one or the other approach have failed or are inadequate—planning and reacting must be fundamentally integrated.

This conception of walking is most appropriate because it formulates a walking robot that is robust to disturbances from the environment and can also be directed to its goal with reasonable efficiency.

When do walking robots need planning? It has been suggested and demonstrated in several systems, for instance [Ferrell95] [Piekenbrock95], that when a leg cannot raise high enough to clear an obstacle, the body should automatically raise up to compound the stepping elevation. However when the robot confronts an insurmountable obstacle, it stands up on tippy-toes, which may be undesirable.

The decision to raise the body higher should not be automatic. In general the body should be maintained at a height planned to clear obstacles. When a stepping leg is found to be vertically limited, a reasoned decision should be made whether and how much to raise the body.

What planning comes down to is perhaps not a sequence of commands. The best result of deliberative reasoning may just be some useful (but temporally-dependent) predictions about the world: regions the legs should avoid (for kinematic and terrain reasons), the height of obstacles in the vicinity, the posture that may be most stable. These predictions are fundamentally what the constraints I developed for Ambler produce.

Architectures for planning and reacting

The case is made, by argument and by experience with previous walking robots, that planning alone, without adaptation during execution, is insufficient for guiding a walking robot in natural terrain. Too much is unpredictable—events, like bumping obstacles or slipping off a precarious footholds, occur and cannot be foreseen while planning.

Behavioral and biological architectures can entail some difficulty in interacting at a cognitive level to produce intentional behavior. Ethological evidence indicates a distinction between intentional and automatic behavior. [Manning92] I suggest a similar organization for controlling walking: planned actions to accommodate predictable occurrences, and automatic reactions for unpredictable events. My approach, like other hybrid planning/reacting architectures (for example [Arkin89a] [Gat92] [Byrnes93]) seeks to capitalize on the advantages of planning for anticipating productive actions, and on reacting for quickly accommodating disturbances in the desired goal state.

Layered or not

If this system were mapped into a subsumption approach I could claim that the basic level of competence is standing, keeping all the feet firmly on the ground, then the next level would be posturing. Above posturing, add stepping, which uses the motions of standing and adds some more. Then above that, walking, which combines standing, posturing and stepping. However, the notion of upper layers subsuming the function of lower layers does not fit such a model. For one example it is the behaviors of standing that inhibit those of walking in order to respond to reflexive corrections. Likewise, regulation of posture effectively modulates the stepping behaviors. Rather than subsuming lower layers, the more complex, or pattern generating behaviors, organize and synchronize the standing and stepping behaviors. Subsumption does not seem adequate, in this case a more fully connected network is at work.

In a similar behavior based controller for the hexapod Hannibal, Ferrell describes a controller of similar complexity based on the subsumption approach. It is clear that behaviors (external apparent task achievers) and agents (internally useful operations) use the mechanisms of the subsumption architecture (inhibition, suppression, excitation), it is not clear how levels of competence are designated, unless walking and all its constituent behaviors are the fundamental level of competence.

Guiding behaviors by planning

The result of planning for a walking robot need not be a prescription of the actions that the mechanism should perform. Instead, it can be to predict appropriate values for the parameters that quantify walking. Predictions like the dimension of nearby obstacles tell the robot how high to lift its feet and how far to stride.

This is supported by two arguments. A negative argument: that gait prescriptions have been a failure. No method has confronted the full complexity of such a planning problem (either in the dimensions of configuration space or the permutations of available gait sequences) and succeeded beyond simulation or structured environments. And a positive argument: planned valuation of gait has been successful in guiding a walking robot.

Getting back to the predictive algorithms developed for the Ambler, now that we have a way of enacting walking, can we improve the performance by utilizing deliberative reasoning. Connell [Connell92] has suggested several ways, including parameterization, to guide behaviors. Others are possible including selectively enabling and disabling behaviors, filtering their input and output (to change response), adjusting their priority or enabling them to learn to improve performance.

By organizing the gait controller around the actuated motions, action parameterization (like the height to raise the legs or the stroke to propel the body) relates directly to those motions, as detailed in Table 7-1. The sensitivity (for example, to contact forces, and to pitch and roll errors) can also be quantified and adjustable. By adjusting these parameters an independent planner can guide the robot, directing its overall performance. This is also the basis of Dante II's supervisory control interface.

Table 7-1: Parameterization of SimPod behavior tasks

Parameter	Position	Velocity	Acceleration	Force	Pattern	Threshold
Body translation	✘	✘	✘			✘
Body height	✘	✘	✘			✘
Body roll	✘	✘	✘			✘
Body pitch	✘	✘	✘			✘
Leg height	✘	✘	✘			✘
Leg force				✘		✘
Gait					✘	

Distributed asynchronous planning

Problems with a single planner operating with multiple constraints is in synthesizing the results. Independent, asynchronous behaviors will use plans. Why aggregate the results if they will be distributed? Instead of multiple planners each reasoning about aspects of independent behaviors, they can operate concurrently. Interaction of the behaviors will combine results as an emergent property.

Formulating planning without command sequences

One of the chief criticisms of hybrid architectures is that they still rely on a planner to select an action sequence. I have detailed the difficulty of obtaining such an action sequence to describe gait. It is necessary to formulate planning without sequences of commands but performance attributes instead.

A pilot for a simulated walking robot, developed by Piekenbrock, learns where the machine can walk.[Piekenbrock95] It uses radial-basis function hidden units in a neural network to correlate visual perception to velocity (forward and backward) and steering angle. The robot's legs detect when it has encountered an insurmountable obstacle and this serves as a training example of what to avoid.

Constraint predicting agents

What I have developed is a decomposition of robotic walking into processes that independently servo control the robot's degrees-of-freedom and cooperatively act to produce a gait. I have also partitioned the gait planning problem to correspond to the attributes of these independent processes (essentially planning single degrees-of-freedom). This allows a planner to avoid the optimizing multiple degrees-of-freedom, and plan just the individual, relevant attributes. Planners can act as independent agents predicting a particular aspect of performance.

Figure 7-1, which builds on Figure 5-13, depicts the essential processes for behavior-based control of walking with plan guidance. Individual behavior processes work collectively to control the various motion servo loops. They used information sensed

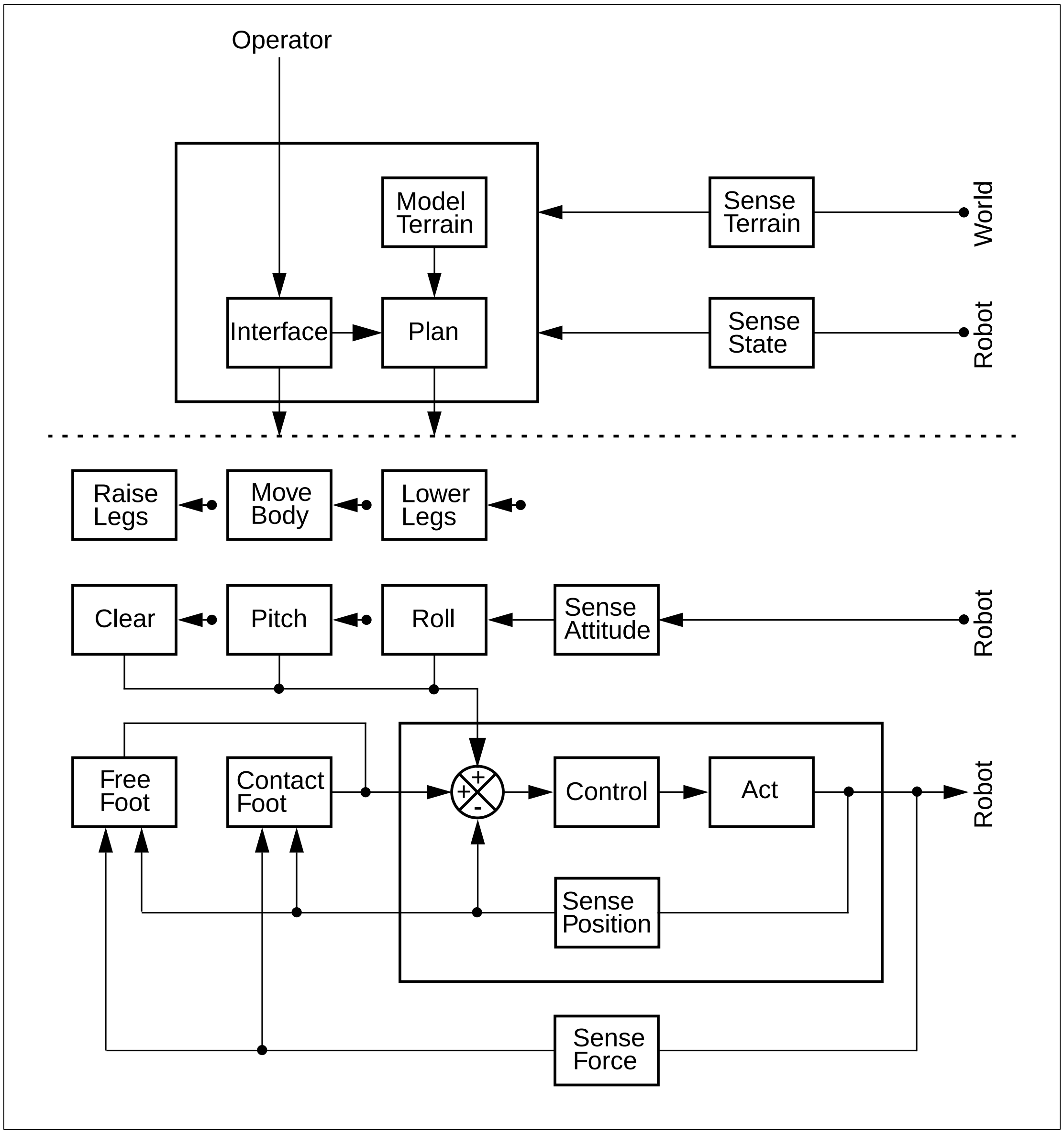

Figure 7-1: Schematic representation of the interaction between planning and behavior.

from the robot—its positions, forces, and posture. The planning process(es) also receive information of robot state (although not about the state of the individual behaviors) as well as perceptual information of the terrain. Planning proceeds by determining those aspects of the terrain that would warrant change in gait. Those changes are affected by updating the parameter values in the appropriate behavior processes.

Adapting to terrain by planning

Implementing this plan guided walking, special planners (agents) determine the appropriate leg lift height for each foot by examining the swept area of the next recovery (to a 30 centimeter radius of the foot).

These foot planners were used to modulate the behavior of the gait controller for the SimPod, using the three sample terrains shown in Figure 6-3. The time history of vertical leg positions, in an anti-metachronal crawling gait, crossing the first terrain appears in Figure 7-2. Unlike when the SimPod walks using only proprioceptive information, here no legs bump obstacles as they swing forward. Instead each leg raises high enough to step above the terrain and then lower down to foot contact. For example, at minute 5, the left middle leg steps up onto a rock. Other clear instances include the left rear leg at minute 33 and the right rear leg at minute 35. In this experiment no rocks are contacted until the leg is lowered down onto a foothold. The foot placements, shown in Figure 7-3, are not identical to those of Figure 6-12, because of the reversal in the leg stepping sequence.

At minute 49 the swept regions of all legs are free of obstacles. A planner watching for this condition switches the gait to a higher speed (but lower stability) tripod gait. Legs raise, in triples, just enough to break contact with the level terrain.

The purpose is to demonstrate simply that an external planner can command changes in gait pattern. The algorithm that the planner uses for this is simple: in flat terrain, select a tripod gait pattern; in terrain with any obstacles, apply a more stable tetrapod gait; and in terrain with many or large obstacles, use a wave gait pattern. The density of obstacles is determined by comparing the variance in the terrain elevation grid to threshold values. Other methods of estimating terrain roughness are possible (for example [Caillas89]), including fractal estimates, but the result is still to trigger changes of gait pattern in response to an externally-identified feature.

With the ability to switch gait patterns on-the-fly, in response to commands from a gait planner, a number of criteria for selecting gait pattern are opened to consideration. For example, as here the pattern can be selected to match stability to terrain roughness. Speed may be the overriding concern at time, and may dictate pattern selection. Mobility may sometimes indicate a particular gait pattern, like a tripod gait for spinning in place, or a free gait for terrain in which many foothold locations are excluded. This gait planner/controller design can produce planned free gaits by inhibiting motion after each step and exhibiting it after the planner plans and parameterizes the next desired step.

The gait through a second terrain appears in Figure 7-4 with foot placements in Figure 7-5. An advantage of continuously adjusting leg lift-off height is that the nominal lift-off can be much smaller, at a level that would be appropriate for clear flat terrain. If no obstacle is detected then this nominal height is appropriate. Many times, minute 1 (left rear), minute 4 (right front), minutes 25 and 35 (left front), and minute 41 (left middle), the terrain ahead is clear and the leg lifts only enough to break contact and step forward.

Because each leg height planner is looking for obstacles along the recovery path and in a radius around the foot rather than just at the foothold there are a number of situations in which the leg raises high up only to be lowered all the way back to the ground, sometimes stepping completely over a rock but sometimes avoiding a phantom. At minute 21 the right rear leg steps over a rock which can be seen in Figure 7-5, bottom centered at 30 centimeter and Figure 7-5, top at (57,30). At minute 20 the left front leg steps high and the lowers to avoid a phantom, a large rock at (42,25) in Figure 7-5 top lies just outside its path. This overheight step is perhaps unnecessary, a balance must be

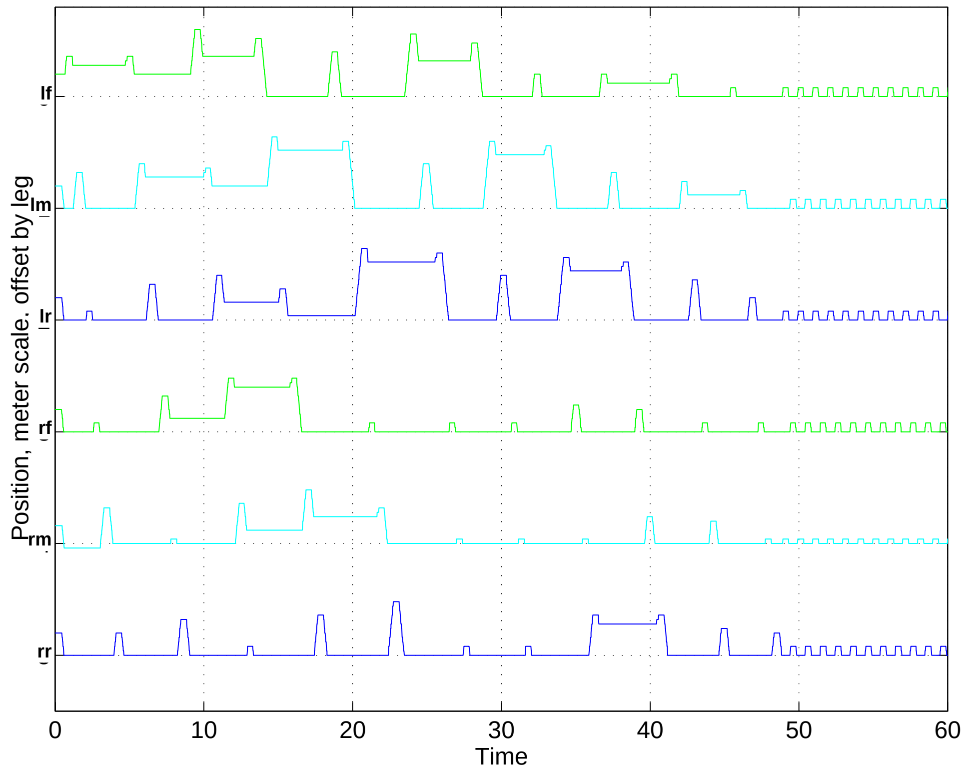

Figure 7-2: Plan guided gait in the first sample terrain from Figure 6-3, top. (Compare with Figure 6-11.)

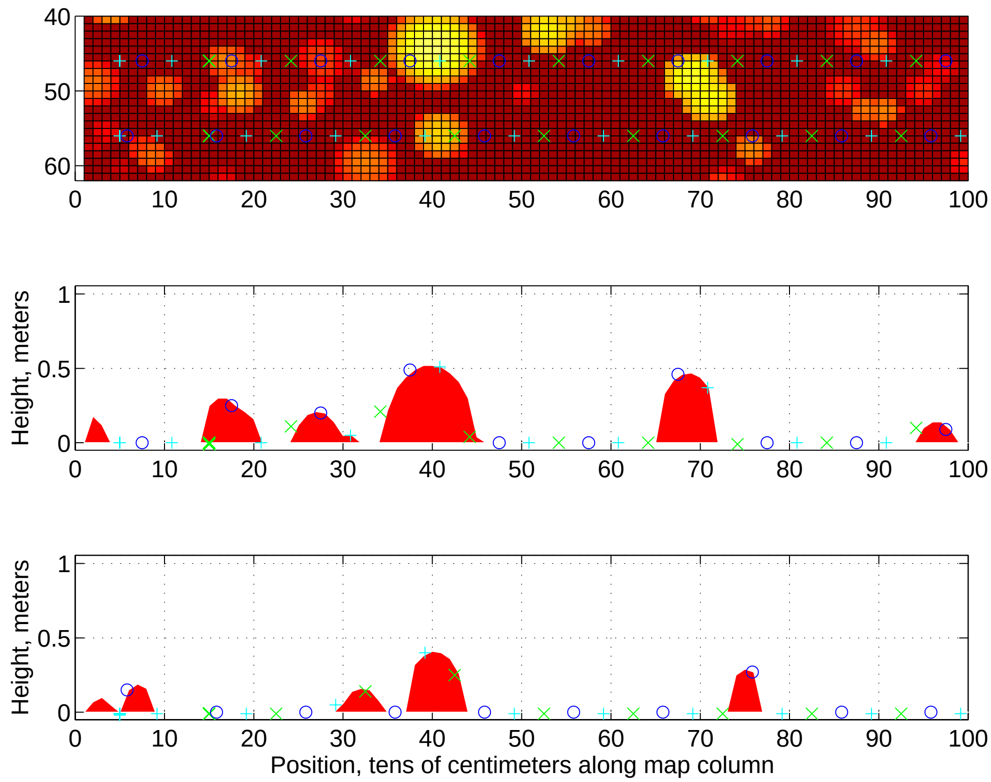

Figure 7-3: Foot placement in first terrain. Plan view (top) with lighter shading indicating higher elevation. Side views of left (middle) and right (bottom) legs: x = front, + = middle, and o = rear leg.

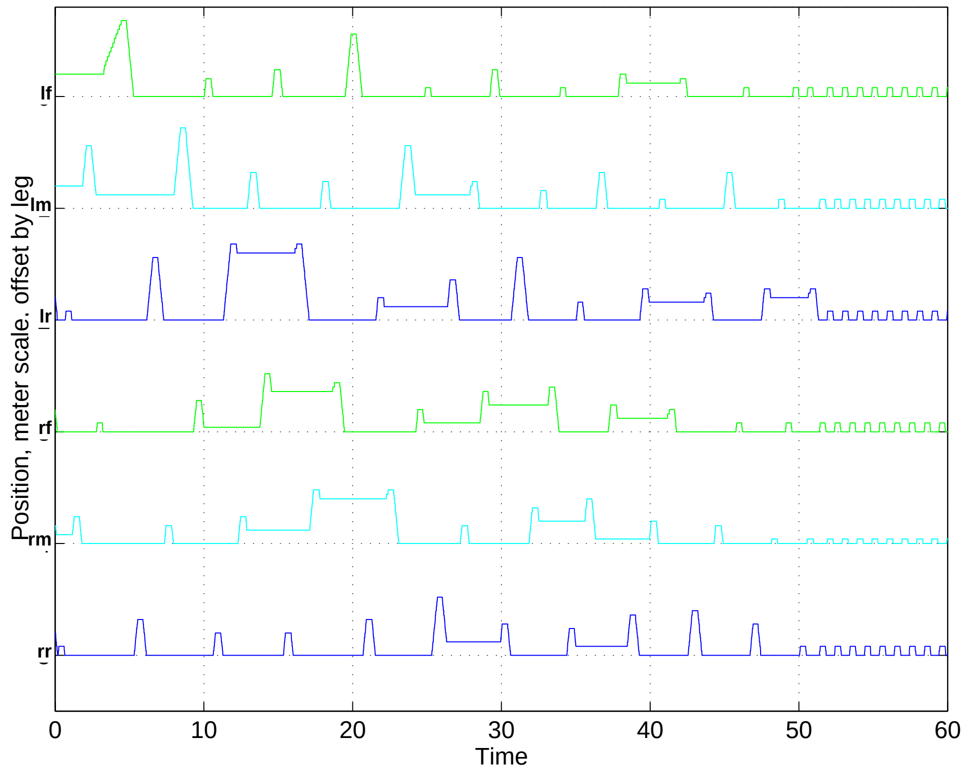

Figure 7-4: Plan guided gait in second sample terrain from Figure 6-3, middle. (Compare with Figure 6-13.)

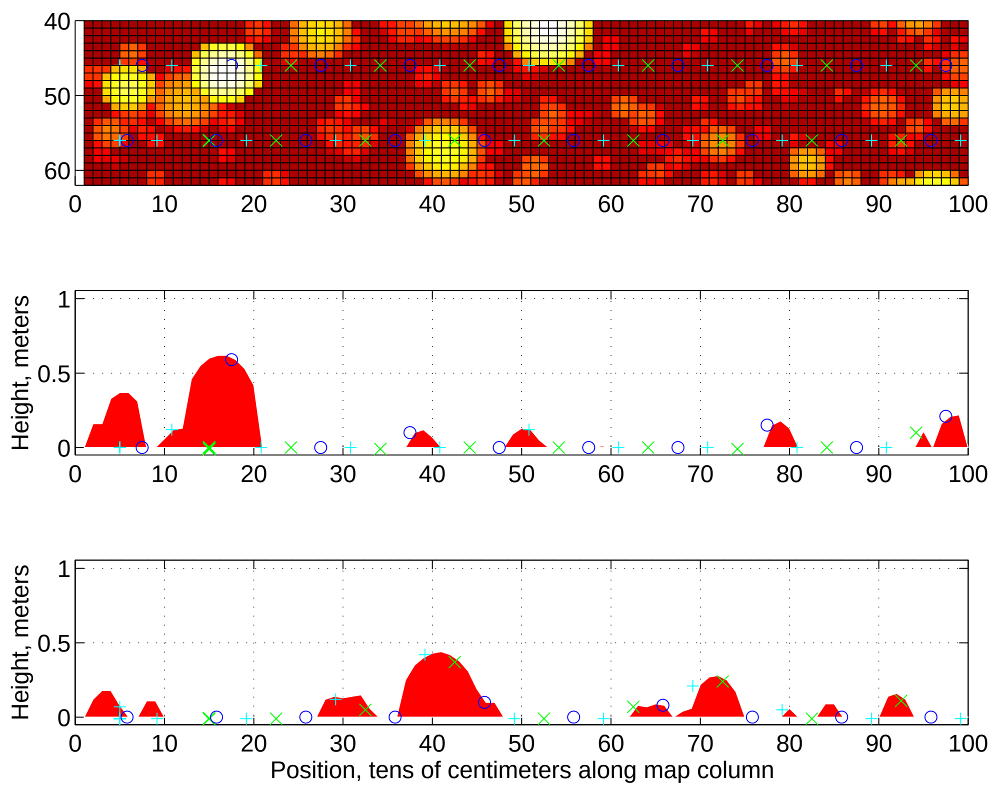

Figure 7-5: Foot placement in second terrain.

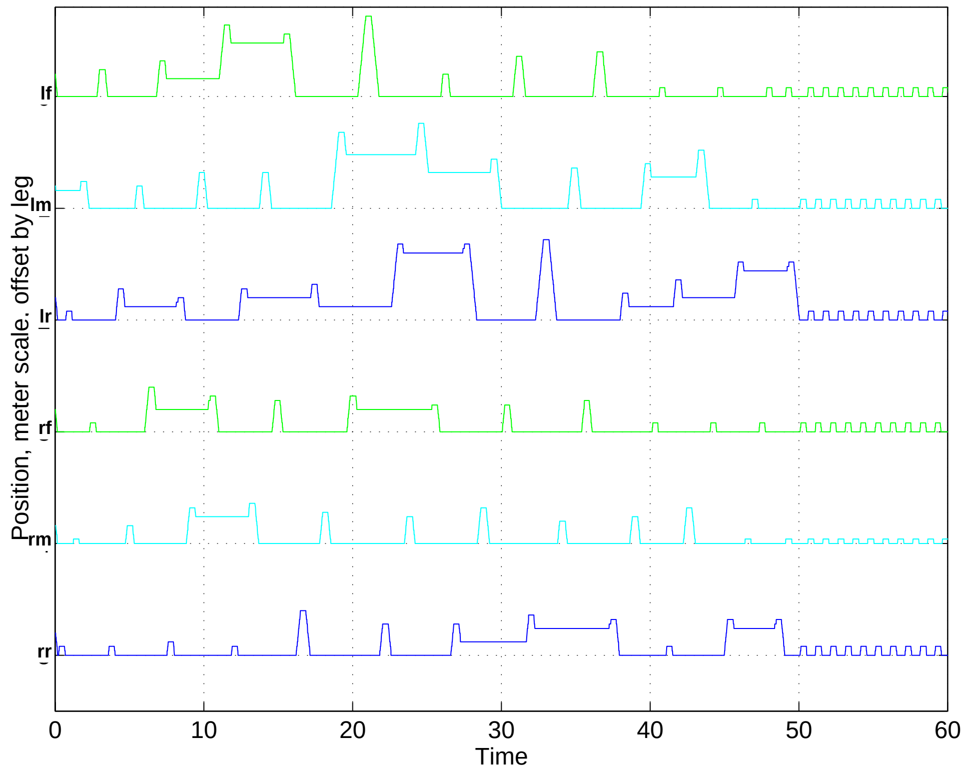

Figure 7-6: Plan guided gait in third sample terrain from Figure 6-3,bottom. (Compare with Figure 6-15.)

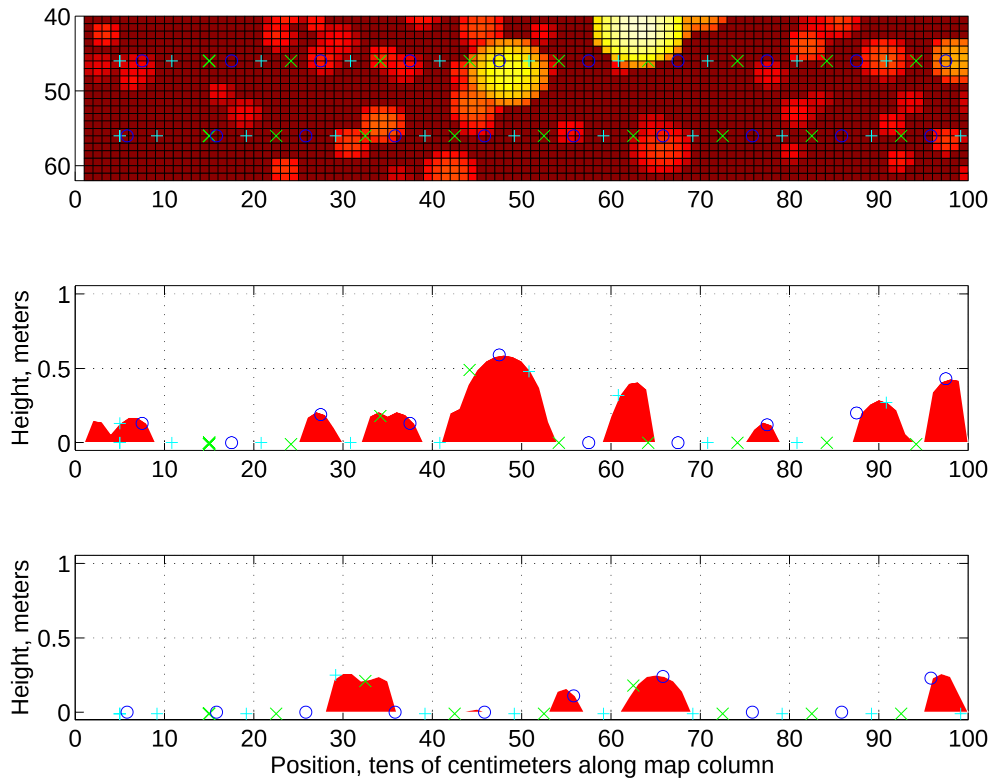

Figure 7-7: Foot placement in third terrain.

struck between the desire to avoid collisions and the cost of extra high steps. Because the proprioceptive bumping reflex will respond to collisions, it is possible to ignore many potential obstacles; a less robust controller must be more conservative.

The gait in the third terrain, Figure 7-6 with foot placements in Figure 7-7, shows similar performance to the previous examples.

Notice that although the step sequence remains fixed, strides are not of uniform speed, their period is adjusted to accommodate the varying time to raise the legs. This is apparent in the changing spacing among recoveries in the right middle leg between minute 17 and 42. In Figure 7-6 between minutes 48 and 52 all legs except the left rear are in clear terrain and quickly step through a complete cycle. The average speed of all three examples is approximately 45 meters in 60 minutes of real time (0.75m/min).

Summary

- Walking robots need to both plan and react. They must plan to anticipate future actions and to foresee the result of current behavior. They must react to sudden disturbances and adaptively produce behavior that cannot be precisely prescribed.
- In the same manner and through the same channels that supervisory teleoperation was achieved with Dante II, plan-guided autonomy can be achieved.
- Planning, not detailed sequences of actions, but defining properties of the gait, produces results that are independent of execution indeterminants and reactive deviations from nominal patterns.
- Terrain maps are used to plan leg lift, body height, terrain pitch, and to select gait pattern. Other extensions are possible and are direct extensions, for example to avoid particular terrain obstacles, adjust stride length, tread width, body elevation and turn rate.
- Behavior-based control combines independent reflexes and provides the mechanism necessary to produce complex patterns of walking. Planning provides external guidance, to adjust the form of walking or to prepare for an anticipated encounter improves the robot’s productivity.

Chapter 8

Conclusion

In **Conclusion**, I will overview what I've done, what it means, and where it might lead. Specifically, I'll summarize the contributions, accomplishments, and future directions that have resulted from my investigation of robotic walking in natural terrain.

Contributions

The purpose of this research has been to find a method of controlling statically-stable robotic walking in natural terrain. In the course of this pursuit, I have made three principal contributions:

- I have created a new behavior-based control method for walking robots, constructed as a heterogeneous network of asynchronous processes. These behavior processes independently control motion by adjusting servo reference values. They enable tactile and postural reflexes that adapt the gait to the underlying terrain, and coordinate robot motions to produce aperiodic gaits. The robot walks autonomously without guidance, but is amenable to supervisory teleoperation. This method has been demonstrated and validated on a real robot in real terrain, specifically, Dante II inside the crater of Mount Spurr. The scale of obstacles and speed of locomotion in climbing sloped, bouldered natural terrain is without precedent.
- I have generalized this method of gait control and established that it applies to different mechanical configurations. It scales to an eighteen degree-of-freedom hexapod that can exhibit multiple gait patterns, including crawling waves, tetrapods and tripods. The behavior network can switch among these gaits on-the-fly, maintaining stability throughout. It spontaneously generates free, aperiodic gaits to correct leg sequencing and avoid kinematic limits.
- I have reformulated gait planning so that instead of planning motions, it specifies the attributes of a productive gait. Further, I have devised a new method by which these

specifications can be used to constrain and guide the performance of a walking robot while still retaining all of the properties of reflexive safeguarding and coordination that behavior-based gait control provides. This allows the robot to foresee changes in the terrain and respond appropriately with changes in its gait.

Accomplishments

The methods devised and systems constructed for this thesis were developed within a context of broader research projects, and were driven by the requirements of particular applications. Consequently, my solutions have focused on real robots in the real world. These robots have accomplished many things. I will summarize some that are significant and in which my work has played a role.

Ambler

- Planned aperiodic gaits for a novel, high degree-of-freedom walking robot
- Walked autonomously (up to 500m) in natural terrain

Dante I

- Demonstrated reactive execution and adaptation of detailed gait plans

Dante II

- Developed behavior-based control of rough natural terrain walking with decentralized, asynchronous coordination of gait pattern, and tactile and postural reflexes
- Enabled supervised teleoperation of a walking robot with low-bandwidth, occasional communication
- Walked autonomous over discrete obstacles, climbing slopes and operating at the mechanical limit of speed performance

SimPod

- Generalized behavior-based control to different mechanical configurations, scaled to more complex kinematics, and extended to multiple gait patterns
- Switched gait patterns on-the-fly, demonstrating stable transitions
- Generated free gaits spontaneously to accommodate kinematic limits and transition between gait patterns
- Demonstrated plan-guided direction of behavior-based gait control

Applications and future directions

This work has resulted in new abilities for walking robots: to produce a variety of gait patterns, to switch among them, and to adapt them freely in order to walk through natural terrain. There are immediate applications for this. The principal motivation for robotic walking has been to provide access to otherwise inaccessible terrain, but additional motivation now comes from concern for impact to sensitive environments and walking over terrain, not driving on it. Capable walking robots hold the promise to replace invasive machinery and fulfill environmental requirements while still performing valuable service.

To apply the techniques used in my work to other applications, the application must be distinguished as individual reflexive reactions and interdependent patterns of behavior. These behaviors need to be parameterized so that reasoned predictions about intended action can affect their performance. Tasks where real-time planning is desirable but intractable lend themselves to reactive control with plan-based guidance.

Serpentine locomotion, like walking, involves rhythmic motions and reflexive behaviors to accommodate terrain irregularities. A network of behaviors could establish the basic pattern of serpentine, concertina, or sidewinding motion, and then tactile reflexes could adapt the motion to push off objects or to brace against them. Like walking robots, it would be useful to be able to guide the behavior of a snake robot. An external planner may able to accomplish this particularly if it can involve just directing the head and letting the body follow reactively.

Robotic excavation suffers from an intractable planning problem in predicting the results of digging operations—the reaction of the terrain is impossible to predict. A network of behavior processes could control the repetitive digging action: biting into the soil, reacting to changes in soil resistance, and pulling out when the bucket fills, and could productively guided the strategy by observing of the result of each action.

A wheeled mechanism with independently driven and steered wheels and active suspension would be an interesting application for distributed behavioral control. Behaviors could independently adjust velocity control servos for traction or energy efficiency—speeding up wheels as they roll over discontinuities and freewheeling wheels in benign terrain. Coordinating behaviors would direct group behavior to climb obstacles, while planners suggest speed and turn rates.

Future enhancements to the details of my gait control method are likely to improve performance. The behavior processes poll sensors and incoming messages but should be interrupt-based for faster response. The behavior processes run near servo rate; some reflexive behaviors could be incorporated directly into the servo loop to further reduce response time. Individual leg force sensors could contribute to posture control. Posture is regulated by the use of inclinometer and leg position, but also considering forces could improve stability by appropriately redistributing loads.

In addition to adjusting the servo references, behaviors could modify the control law itself, changing the transfer function gaits. This sort of adaptive control, modulated by behaviors, could operate in decentralized manner, like neuromuscular systems which exhibit impedance control. Behaviors could provide compliance while the leg swings, stiffness while it supports.

The gait planning, now appropriately partitioned, could expand to address modification of the robot trajectory to avoid obstacles. This has long been a goal but has been secondary to achieving reliable walking.

The method of gait planning and control developed in this thesis is validated on an actual robot, Dante II, and generalized to an 18 degree-of-freedom hexapod. It appears that there are no scientific barriers to building a new generation of walking robots that can adapt their gait to terrain, change gait patterns to adjust speed and stability, and walk autonomously through natural terrain. This new generation of walking robots may climb mountains, cross deserts and seabeds, and explore planets.

Glossary

Following are terms related to legged locomotion or gait. They appear in the text, or are of general significance. Words found below in ☞ *this font* have their own entry.

ambling Ambling is the *running* form of a walk gait in which there is a short ballistic phase. Elephants amble.

basogram A basogram is a chart that plots leg-ground contact versus time. Basograms are used to depict gait pattern by clearly showing which legs are on the ground at any given time.

bounding In a bounding gait the front legs move together in phase and then the back legs move together in phase (or, in some animals, slightly out of phase). A bounding gait is demonstrated by the inch-worm. See also [Alexander84].

canter In a canter gait one pair of diagonally-opposed legs moves together in phase while the other pair(s) move a half-period out of phase with respect to each other. The canter is asymmetric and must often be trained. See also [Alexander84].

circulating A gait is circulating if leg *recovery* occurs from the rear of the body to the front. There are no naturally occurring circulating gaits but some appropriately configured robots, for example the Ambler, can perform it.

conservative support polygon The conservative support polygon (CSP) is the region in which the center of gravity must be positioned for the walker to be stable when any single leg fails. It is the intersection of n-1 *support polygons* formed by individually eliminating each of the n *supporting* legs. See also [Mahalingam88].

contralateral A contralateral leg is the corresponding leg on the symmetrically opposite side of the body.

crabbing A gait is described as crabbing if body motion is not parallel to the longitudinal axis of the walker. When exhibiting a crabbing gait, the walker moves sideways, like a crab.

crab angle The crab angle is the angle between the direction of motion and the *sagittal* plane of the body.

crawling A crawling (or creeping) gait has only one leg in the *recovery phase* at a time.

creeping See crawling.

cursorial Cursorial means literally "adapted to running" and can be used to identify *running* gaits, or walkers that are capable of *running* gaits.

cycle time The cycle time is the time for the complete cycle of a *periodic* gait—each leg is returned to the same relative position. See also [Song87].

duty factor The duty factor of a leg is the fraction of the gait's *cycle time* that a leg is in the *support phase*. See also [McGhee68a] and [Song87].

energy stability margin The energy stability margin is the minimum energy required to tip over a walker. It is the energy needed to rotate the center-of-gravity of the walker around the least resistive edge of the *support polygon* to the point where the center-of-gravity is directly above this edge.

fixed See periodic.

follow-the-leader Follow-the-leader (FTL) describes a gait in which trailing legs step into the footholds vacated by leading legs. Millipedes use a follow-the-leader gait.

free A gait is free if any leg that is not necessary for *support* is permitted to move at any time. Free gaits are aperiodic, irregular, and not often exhibited in the natural world. The origin of the term is attributed to [Kugushev75].

gait cycle See stride.

galloping Galloping is similar to *bounding* except that the front and rear legs are slightly out of phase with each other. The slight phase offset can be added to legs on one side (transverse galloping) or to a diagonal pair of legs (rotary galloping)

ipsilateral Ipsilateral means on the same side. "Ipsilateral legs" refers to legs on one side of the body.

lateral stability margin The lateral stability margin is the shortest distance between the vertical projection of the walker's center of gravity and the side (lateral) edges of the *support polygon*. See longitudinal stability margin.

leg cycle See step.

longitudinal stability margin The longitudinal stability margin is the shortest distance between the vertical projection of the walker's center of gravity and the front or rear (longitudinal) edges of the *support polygon*. See also [Özgüner84]. See lateral stability margin.

metachronal A metachronal *wave* travels in the direction of the walker's movement. In the context of walking, metachronal is often used to describe the *wave* of leg activity as it proceeds from the posterior to anterior legs.

pacing In a pacing gait, legs on the same side of the walker move simultaneously. Pacing (or racking) is most commonly exhibited by camels.

periodic A gait is periodic if each leg retraction takes the same amount of time and occurs repeatedly at the same time in the locomotion cycle.

pitch The pitch is the longitudinal distance between the foot placements of *ipsilateral* legs.

pose Pose is the position and orientation of the walker in the world. More specifically, it is the position and orientation of the internal body reference frame (local) in the external world reference frame (global).

pronking In a pronking gait, all legs move simultaneously in phase. It is most commonly seen in gazelles.

protraction Protraction means to extend forward or outward, usually in the direction of motion, like the leg does during the swing (*recovery*) phase.

racking See pacing.

ratcheting Ratcheting (also ripple) is a *wave* gait in which leg *recoveries* alternate sides of the walker as they propagate along the body. A hexapod displaying a front-propagated ratcheting gait moves its front leg first, then its opposite-side middle leg, then its rear leg. A rear-propagated ratcheting gait would occur in the reverse order.

recovery Recovery (leg recovery) is the action of taking the foot out of contact with the terrain, moving it to a new foothold, and reestablishing contact with terrain.

recovery phase The recovery phase (also swing phase, transfer phase, or return stroke) is the period of the *gait cycle* that the foot is not in contact with the terrain.

regular A gait is regular if all legs have the same *duty factor.* [Song87]

relative phase The relative phase between two legs is the fraction of a *stride* by which the placement of one leg on the ground lags behind the placement of the other leg.

retraction To draw back, backward or inward, usually against the direction of motion, as the leg does during the propelling *(support*) phase (the feet don't move with respect to the ground, however).

rotary galloping See galloping.

running A gait is distinguished as running when pairs of legs have *duty factors* less than half of the *stride*. This indicates that there are periods, called ballistic or flight phases, when both legs in a pair are off the ground (in the *recovery phase*).

sagittal Sagittal refers to the median plane of the body—the plane front to back that divides the body into, usually symmetric, left and right sides; also occasionally the side-to-side plane that divides a body into front and back ends.

singular A gait is singular if two or more leg set-down or lift-up events occur simultaneously.[Song87]

stance A stance is any specific configuration of the joints of a walker—a point in configuration space. It is a description of the actuators in an internal reference frame, for example the Cartesian position of all the legs relative to the body. Stance alone sometimes refers to both stance and *pose*.

stance phase See support phase.

static stability margin The static stability margin is a measure of the minimum distance from the vertical projection of the center of gravity to an edge of the *support polygon*. It is the minimum of the *lateral* and *longitudinal stability margins*. See also [Messuri85].

step A step (also leg cycle) is the cycle of motion of an individual leg from a reference position (usually the beginning of the *recovery phase* or the middle of the *support phase*) through *support* and *recovery* back to the reference position. It is the complete *protraction* and *retraction* of one leg.

stride A stride (also gait cycle) is a complete cycle of motions such that each leg is *recovered* at least once. It spans the interval from the beginning of the *support phase* through the *recovery phase* and to the next beginning of the *support phase* for some reference leg. Typically, each leg cycles once per stride; natural animal gaits are nearly always like this. [Alexander84]

stride length Stride length is the distance traveled by a reference point on the walker during one complete *stride*. It almost always equals the leg *stroke*.

stroke Stroke is the distance that the foot translates relative to the body during the *support phase*. It is the *retraction* length and also the length of body advance.

support Support is the action of maintaining the foot in contact with the terrain and bearing load.

support phase The support phase (also stance phase or power stroke) of a leg is the interval of the during which the leg *supports* the body and propels it forward.

support polygon The support polygon (also support pattern) is the convex hull, the minimum bounding polygon, of the vertical projections of the *supporting* legs.

swing phase See recovery phase.

symmetric A gait is symmetric if the *recovery phase* of each left-right pair is a half-cycle out of phase. [Song87] This does not necessarily correspond to mathematical symmetry. See also [Collins92a].

tetrapod A tetrapod is a group of four legs. In the tetrapod gait of an octopod, four legs *support* the walker while the other four legs simultaneously *recover*. In the tetrapod gait of a hexapod (also ripple or parallelogram gait), four legs *support* while two legs *recover.*

transfer phase See recovery phase.

transverse galloping See galloping.

tread The tread is the distance from the *sagittal* plane to the foot.

tripod A tripod is a group of three legs. In the tripod gait of a hexapod three legs that enclose the center-of-force *support* the walker while the other three legs simultaneously *recover.* A hexapod's *ratcheting* gait is a tripod *crawling* gait.

trotting In a trotting gait, diagonally-opposite pairs of legs move simultaneously in phase. One pair moves a half-period out of phase from the other. The trot is a *running* gait so the legs have a *duty factor* less than one half.

walking A gait is walking when the *duty factor* for all the legs is greater than half the *cycle time*. This indicates that there are periods, called double-stance, when both feet in a pair are on the ground (in the *support phase*). For quadrupeds, there are times when both legs of a front or back pair are on the ground; each leg moves one quarter-period out of phase in an alternating *wave*.

wave A gait is a wave if the initiation of *recovery phase* progresses sequentially along the body—a leg's *recovery* begins immediately after an adjacent neighbor's but before the other's. This wave can propagate from the rear (called rear-propagating, forward or *metachronal* wave) or from the front (front-propagating or backward wave).

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