Developing planning and reactive control for a hexapod robot

David Wettergreen and Chuck Thorpe
The Robotics Institute
Carnegie Mellon University
Pittsburgh, PA 15213-3891 USA

Abstract

We have designed an architecture that allows a gait planner to effectively control primitive walking behaviors. The behaviors ensure safe and efficient walking, even without planning; the addition of planning improves performance in rough terrain by allowing the robot to anticipate changes in its gait. We have implemented our approach and demonstrated it on a real robot, Dante II, and on a simulated hexapod with more complex kinematics. With the hexapod we can produce a variety of gaits and stably switch among them. We have attained performance improvement by using narrowly focused planning to guide behavior.

1 Introduction

A substantial portion of the Earth is inaccessible to wheeled mechanisms—natural obstacles like large rocks, loose soil, deep ravines, and steep slopes conspire to render rolling locomotion ineffective. The sea floor, moon, and planets are similarly challenging. In natural terrains, legs are often superior to wheels; they avoid undesirable footholds and make discrete contacts where wheels must propel with continuous rolling contact. [1] Legged mechanisms surmount terrain discontinuities of body-scale rather than wheel-scale and can isolate their posture from the terrain, minimizing power and maximizing stability. [2]

There is a demand for exploration and operation in natural terrains that walking robots are uniquely able to meet. An impediment to supplying this demand remains the difficulty of controlling the robot's gait. We have focused on this and developed architectures for several walking robots, most recently for the robot Dante II. [3]

We have expanded the behavior-based architecture developed for Dante II, shown in Figure 5, to control a free-gait hexapod that has more complex kinematics and the ability to perform a variety of gaits. Our architecture allows a gait planner (or human operator) to guide primitive walking behaviors.

Like Dante II, this new hexapod generates its gait with task-achieving behaviors. These behaviors interact with servo loops, and are parameterized and instantiated by planners. They ensure safe and efficient walking, even without planning; the addition of planning improves performance in rough terrain by allowing the robot to anticipate changes in the style and form of its gait. With this hybrid approach we achieve fundamental capability and then greater efficiency.

Figure 1: Dante II descending into the crater of Mount Spurr.

In this paper we describe the design of the walking behaviors, their capabilities, and the first results obtained when a planner provides guidance to individual behaviors.

2 Controlling walking with behaviors

What we want to do is control and coordinate the many degrees-of-freedom of a legged robot so that it is robust to disturbances and also productive as it walks through terrain. Some legged mechanisms are small enough so that impact dynamics do not adversely affect them, and so they need not be carefully controlled or stable to walk. However, we would like to grow these devices to carry larger payloads, operate for extended periods, and perform complex tasks. Our strategy is to avoid violent collisions and destabilization, and to establish stable servo control over each motion. The problem becomes one of appropriately generating reference values for each servo loop.

We have approached this problem in the past, notably for the Ambler robot, with a monolithic planner that senses and models the terrain, plans a coordinated sequence of actions, and decomposes these actions into servo position commands.[4] This approach has a number of difficulties, principal among them is that it is too slow and complex to keep up with the pace of the environment; as the robot walks its forceful interaction with the environment causes rapidly evolving events like bumps, slips, and tips. It is well-established now that behavior-based methods, which simplify the situation by more directly mapping the sensed stated of the world into actions, speed up response time.[5] These approaches also offer a way to simply and quickly generate servo references. One description of behaviors is as "smart servo loops".[6] To control and coordinate the robot's gait we use behaviors to drive servo control.

2.1 Behaviors drive servo control

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. Behaviors, implemented as concurrent, task-achieving processes, embody these abilities. They act independently to achieve or maintain desired states, and interact to walk.

The *contact foot* behavior, depicted in Figure 2, is an example of a task-achieving behavior. It causes the foot to achieve and maintain contact with the ground. The *contact*

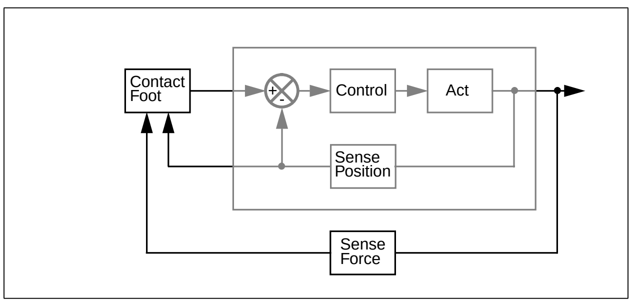

Figure 2: The *contact foot* behavior, a single concurrent process, duplicated once for each leg, senses position and force information and produces a servo reference to maintain foot contact with the ground.

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 moves downward until contact is restored. The *contact foot* behavior initiates each support phase and applies when a foot slips or the terrain crumbles.

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 replanning activity. In our approach, when the intention to place a foot on the ground is established, *contact foot* will keep trying to achieve and maintain that intent. What we have found is that the robot eventually reaches the desired state despite the frequent interruptions that occur during walking.

2.2 Behaviors interact to embody walking

We implemented a behavior-based gait controller of asynchronous processes: eight *contact foot* behaviors to stand, *roll, pitch,* and *clearance* behaviors to posture, eight *free foot* behaviors to step, and one each of *raise legs, move body,* and *lower legs* behaviors to walk. These behaviors are networked by links that carry inhibit and exhibit control messages (specifically inhibit enable and disable, and exhibit enable and disable, each two bits). Each process has the same structure: it executes a non-terminating loop waiting for an incoming exhibit or inhibit message. The inhibition/exhibition logic is simply, "exhibit when receiving one or more exhibit message and no inhibit messages." When the process exhibits its behavior, it watches for signalled events and sensed conditions, and produces signals and actions. The arbitration among competing behaviors occurs explicitly; when one is exhibited it directly inhibits those with which it competes for resources. Figure 3 depicts *contact foot* and additional behavior as they contribute to the leg position servo reference.

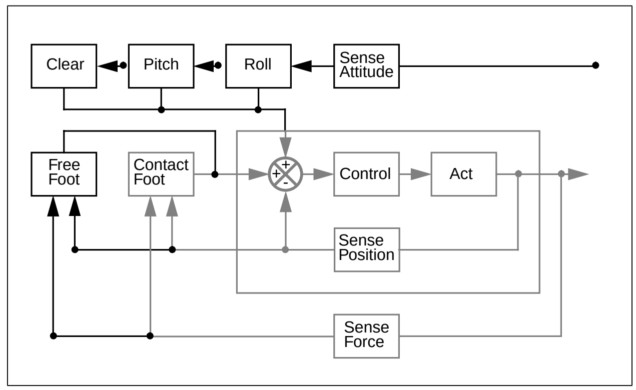

Figure 3: *Free* and *contact foot* behaviors are mutually exclusive and trade production of a servo reference. *Roll*, *pitch* and *clearance* behaviors sense body attitude and incrementally adjust the servo reference.

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 affect 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 acceptable motivation for a pitch adjustment). In Figure 3, 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 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.[3]

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*, *move body*, 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 *move body* behaviors, which controls the body position servo reference, and, in turn, signals the *lower legs* behavior, completing the one step cycle.

2.3 Dante II walks in volcano terrain with behavior-based control

We implemented this behavior-based gait controller on the walking robot Dante II, which descended into the volcanic crater of Mount Spurr, Alaska. Figure 4 presents data recorded during Dante II's descent into Mount Spurr. It

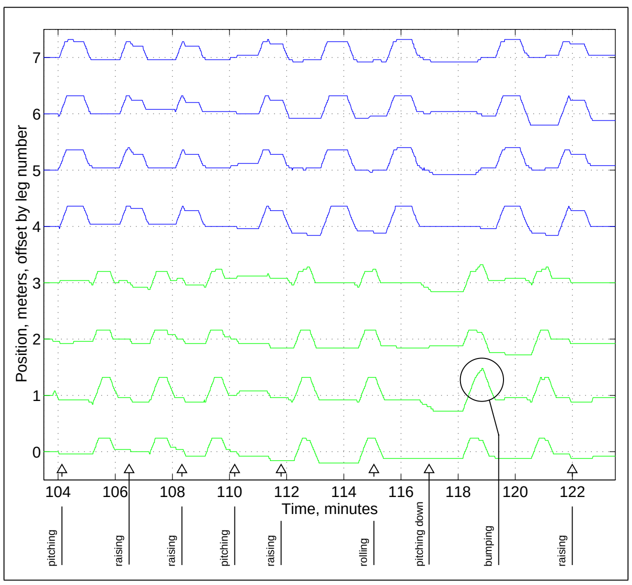

Figure 4: During Dante II's descent into Mount Spurr, behaviors enabled walking while concurrently adjusting body pitch and height, and reacting to bumps.

depicts the height of Dante II's legs, each on a different line, over a period of time. In groups of four (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. At times, for example minute 110, the robot adjusts its pitch: front legs (0,2,4,6) move down, rear legs (1,3,5,7) move up. The entire mechanism may raise, as at minute 106, when all legs lower. When free legs contact obstacles, as at minute 119 on leg 1, the leg raises until it is free.

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. This, we believe, validates our approach to behavior-based gait control for a frame-walking robot.

3 Generalizing to a free-gait hexapod

Dante II presents a somewhat restricted form of walking: frame-walking, in which leg groups move in conjunction. We have expanded our scope to a more general free-gait hexapod, shown in Figure 5, to further test the viability of our architecture, perform a variety of gaits, and begin to address free gaits which are necessary both for spontaneous fixed gait transitions and for extremely rough terrain.

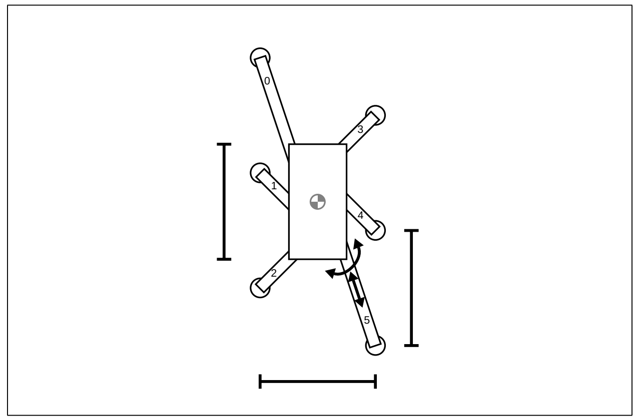

Figure 5: The free-gait hexapod has 18 degrees-of-freedom and stride, tread, step height, and body length of equal scale.

3.1 More degrees-of-freedom requires more coordination

In addition to the behaviors described for Dante II we designed new behaviors to deal with the added degrees-of-freedom (18 versus 10) and the possibility of performing a variety of different gaits. We implemented six *step leg* behaviors to stroke legs individually, and reduced our network to six *contact leg* and six *free leg* behaviors.

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. Strictly, this means that the center-of-gravity must always be enclosed by a polygon of supporting legs. Practically, it can be achieved by keeping the adjacent neighbors of each free leg on the ground. A *support* behavior does just that. 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.

Finally, we extended the capabilities of the *raise legs* behavior and added minimal internal state. *Raise legs* now 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. *Raise legs* stores which gait pattern it is applying and the last leg(s) moved. In Figure 6, a stable crawling gait and faster tetrapod gait show the ability of the hexapod to perform different gaits. Other mechanisms can perform a variety of gaits like these, for example [7] and [8], but their control only allows transition as a continuous function of stepping frequency. Our behavior-based controller can change arbitrarily among gaits and spontaneously produce free gaits to maintain stability.

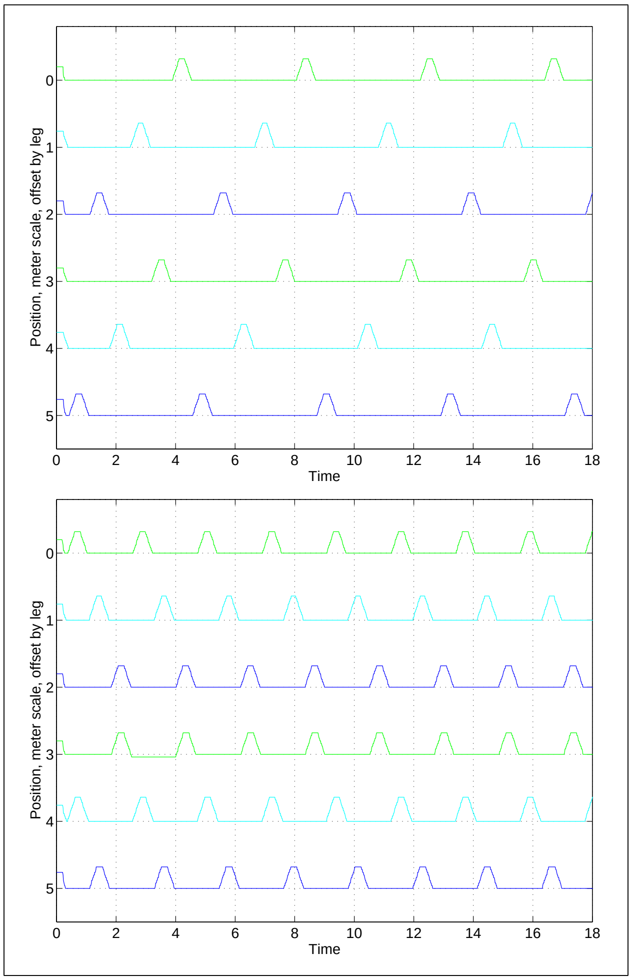

Figure 6: The hexapod can produce a variety of gaits including crawling wave gaits (top), tetrapod gaits (where legs 0&4, 1&5, and 2&3 step together while four legs support) (bottom), and tripod gaits.

3.2 Free gaits allow greater adaptability

A free gait is an unrestricted sequence of steps in which any leg can move at any time. Free gaits enable rock-hopping through extremely rough terrain and the maneuvering required to crawl through dense obstacle fields. Free gaits also smooth the transition from one gait pattern 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 (shown in Figure 7 along with corresponding gait speeds).

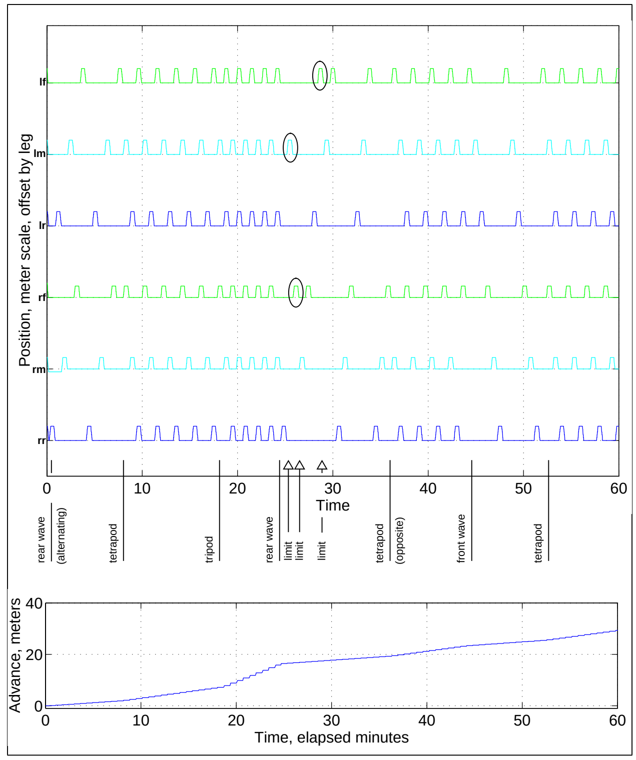

Figure 7: Switching gaits requires constant stable support and spontaneous free gaits to correct leg motion limits that occur during transitions. Modified basogram (top) and rate of progress (bottom).

4 Integrating planning

Walking robots need fast reaction to survive bumps and slips, but also foresight and planning to be productive and efficient in an unstructured environment. Architectures that hybridize planning and reacting have gained some acceptance among pragmatists because of their potential to combine these properties.[9][10] Our hexapod's control system applies a hybrid approach in which narrowly focussed planners modify individual behaviors to change their performance. In this manner, legs step higher as the terrain gets rougher, and change gait if their speed can be increased.

4.1 Walking blindly through natural terrain

To validate the hexapod in natural terrain we generated realistic terrain patches using Moore's model.[11] The number of rocks per unit area of a given radius is estimated by $\beta(\text{radius}^{\alpha})$, where $\alpha = -2.66$ and $\beta = 0.013$ are determined empirically (in our case from Viking lander photographs).

Comparable to the performance of Dante II, the hexapod can perform a crawling wave gait through rough terrain with only proprioceptive sensing. This is shown in Figure 8 with foot placements shown in Figure 9. As the robot encounters rocks, the legs bump and raise up.

In Figure 10 gaits switch as the robot continues to react to rough terrain. At some times, for example minute 18, the

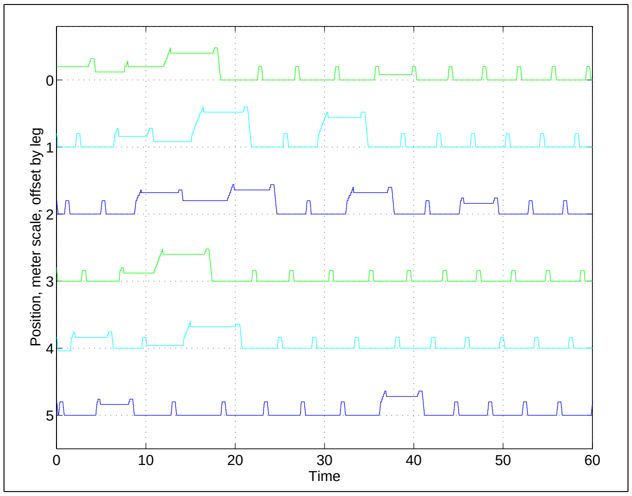

Figure 8: Walking through terrain the leg height over time shows the legs lifting up and stepping down, sometimes on rocks. A slow rise indicates that the foot has bumped a rock and is stepping over it.

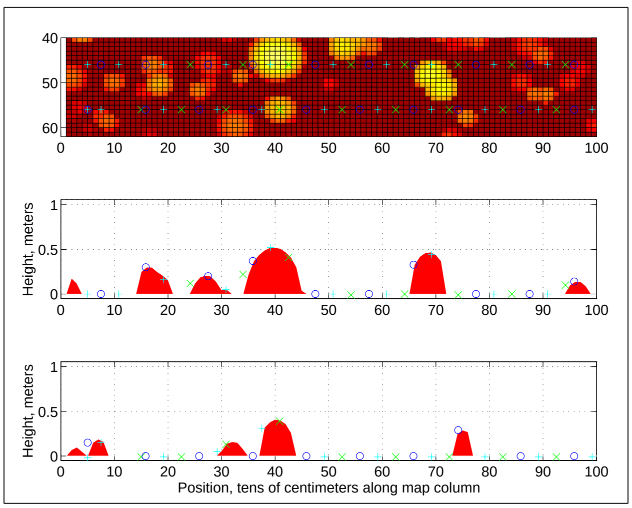

Figure 9: Terrain elevation (top) and foot placements of left legs(middle) and right legs (bottom).

change in fixed gait pattern transition is eased by eliminating repeated recovery of the same leg. This behavior is enacted by *move legs* which stores the last recovered legs.

5 Integrating planning with behavior-based walking

We have established that behavior-based control alone can produce robust walking. Dante II walked in the mode for up to 3 hours at a time with an average speed of 0.51m/min. It sprinted to 0.67 m/min which is about three times the speed of an experienced human teleoperator.[3] Our hexapod can similarly struggle through rough terrain, although it invariably bumps into every rock above its nominal step height.

Dante II demonstrates another lack of foresight: when approaching an abrupt change in slope it is desirable for structural and stability reasons to divide a pitch adjustment over several steps, but without foreseeing the impending

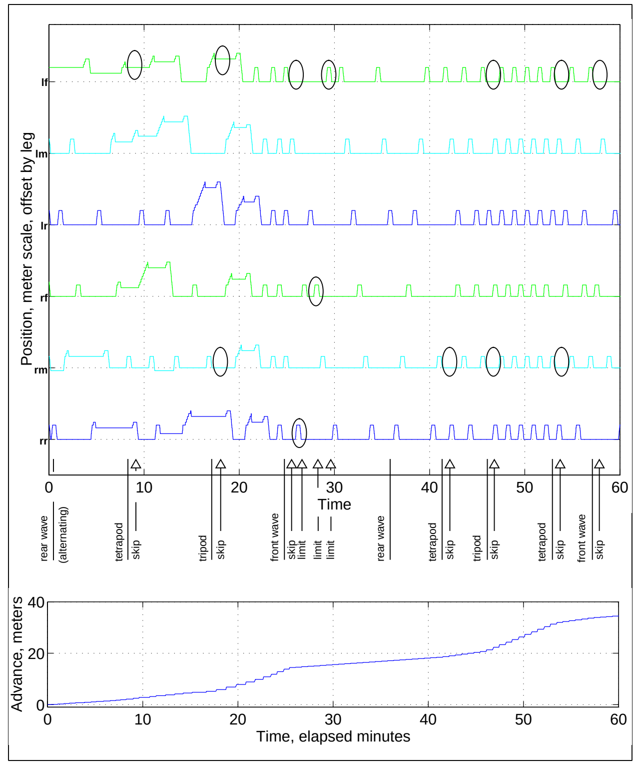

Figure 10: In rough terrain, delays occur while individual legs surmount obstacles. There is a prohibition on picking up the same foot twice in a row.

change there is no way to anticipate and begin adjusting the pitch. Similarly, when encountering an insurmountable obstacle: if seen in advance, the obstacle can be avoided with a slight turn, but when confronted directly, many, inefficient maneuvers are necessary for circumnavigation.

All these situations require some foresight, a property that purely behavior-based approaches lack. With sensing and prediction, simple foresight, the robot can minimize bumping, decrease impacts, reduce delays, provide safer operation, reduce unnecessary conservatism in gait, and see when to switch to faster but less stable gait.

We integrate planning by parameterizing each behavior. For example, the *free leg* behavior is parameterized by how much to lift the leg and what force constitutes a bumping contact. The desired roll, pitch, clearance, gait, and generally, positions and forces can be instantiated by default, by a human operator, or by an independent planner. The planner(s) operate on information perceived from the world (which, to date, is represented as an elevation grid) and the current state of the robot, shown in Figure 11.

Narrowly focused planners examine the external and internal state to predict, for example the necessary body clearance, and then change the value of these parameters to guide the robot. If the planner fails or is too late, the robot still walks robustly. But if the planner predicts a value correctly, performance improves: collisions decrease and feet more closely follow the terrain. In Figure 12 the dramatic

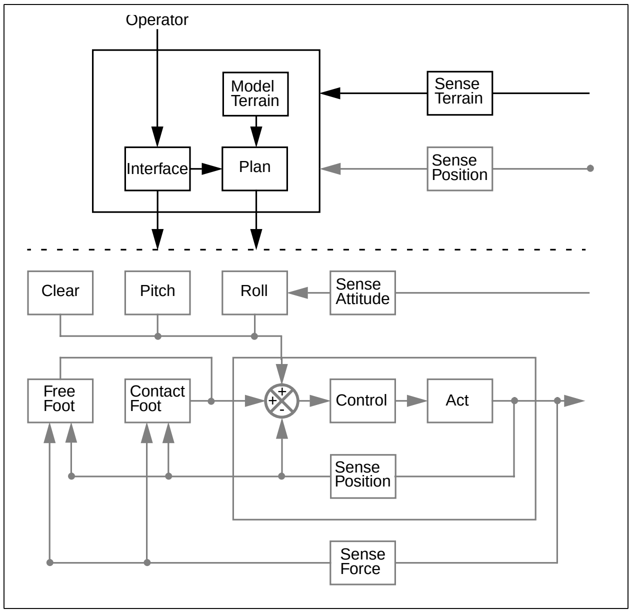

Figure 11: The operator and planner(s) guide the gait controller by predicting and setting parameters.

decrease in the number of terrain collisions is apparent. By

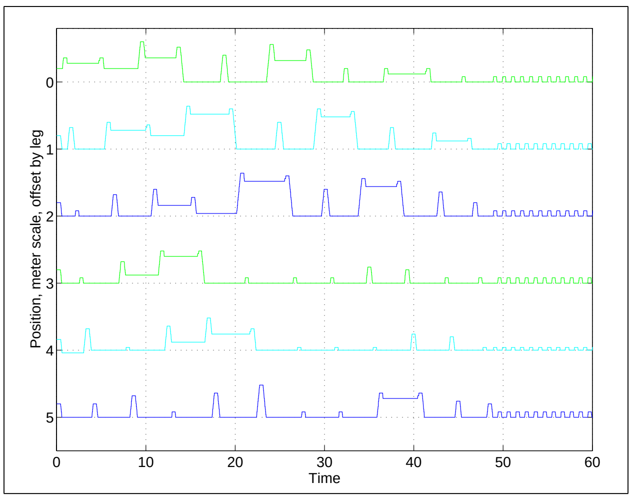

Figure 12: With a planner guiding the behaviors, leg heights adjust in advance so that bumps occur less often; compare to Figure 8. In smooth terrain the step height is reduced and the gait changed to tripod.

operating from a model of the world, a planner predicts appropriate step height. The feet step onto some objects, and up and over others. In clear terrain legs raise only slightly. Another planner switches to a faster tripod gait (minute 49) when the path ahead is clear. The average speed is 0.47 m/min, versus 0.23 m/min without planning.

6 Summary and conclusions

Working from the architecture implemented and demonstrated on Dante II, we have added behaviors and extended its applicability to a general free-gait robot. The architecture supports a variety of fixed gaits and spontaneously produces free gaits to enable transitions between fixed gaits. We have further improved its performance by applying narrowly focused planners to guide the behaviors.

Although the architecture was validated on a real robot, Dante II, the hexapod work is performed in simulation. We built the hexapod with a real-time operating system to maintain some fidelity. Turning, stride length adjustments, and implementation on a real hexapod are obvious extensions without specific impediments.

We believe that the performance of the hexapod, walking in natural terrain, switching gaits, and being guided by planners validates our approach and makes general-purpose walking machines a feasible future development.

7 Acknowledgments

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