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Behavior-based Gait Execution for the Dante II Walking Robot

David Wettergreen, Henning Pangels, and John Bares
The Robotics Institute
Carnegie Mellon University
Pittsburgh, PA 15213-3891 USA

Abstract

The Dante project is developing walking robots to explore inside volcanic craters. These robots face many challenges including generating a walking gait in rough, obstacle-filled terrain. For the walking robot Dante II, we implemented a gait controller to address this situation. Our approach is embodied in a network of asynchronous processes that establish a fundamental gait cycle while maintaining body posture, and reacting to bumps and slips. We describe our implementation, and its relation to similar behavioral approaches, and discuss Dante II's performance during testing and on its descent into Mount Spurr.

1 Introduction

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 II entered the active crater of Mount Spurr, Alaska in July 1994. Shown in Figure 1, it measured gasses and temperatures, and observed fumaroles on the crater floor.

Walking has certain advantages over rolling[1], and on rough, steep escarpments a walking robot is well-suited. Walking does pose unique problems; generating a coordinated sequence of leg and body motions, a *gait*, is one such problem, and is the topic of this paper.

We can formulate gait generation in two distinct but related parts: *planning*—the identification and prescription of future actions from goals and predicted events, and *executing*—the enabling of immediate actions to walk and to maintain safety and stability when confronted with unexpected events.

This paper concentrates on the latter, on executing gaits, and the design and implementation of our approach. It is embodied in a network of asynchronous processes that establish a fundamental gait cycle while maintaining body posture and reacting to bumps and slips. These processes, which embody specific behaviors, are parameterized so that they can be modified and guided by external planners or operators.

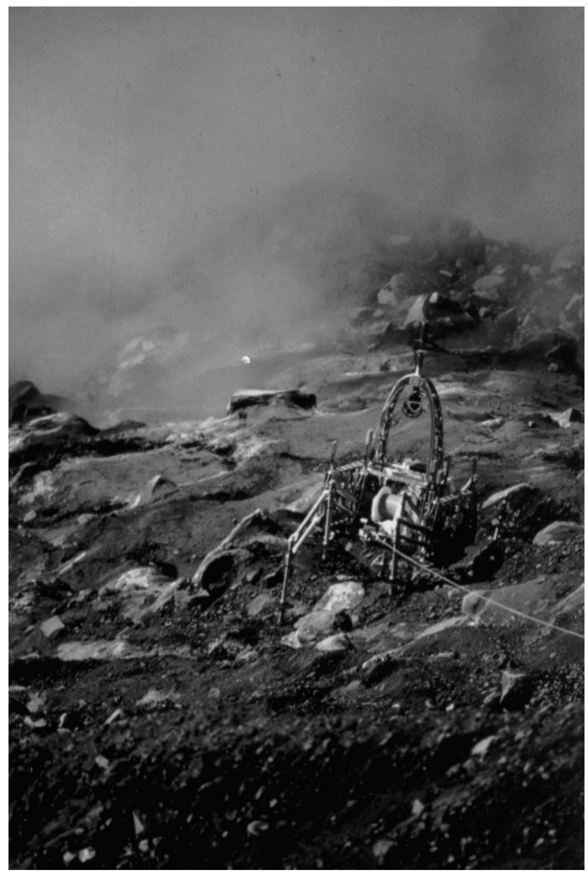

Figure 1: Dante II on Mount Spurr's crater floor

Dante II has undergone rough-terrain testing, ascending and descending slopes (up to 50°) of slag, gravel, and boulders. On Mount Spurr, it experienced snow, wet ash, and mud. We conclude with observations from these experiments and comments regarding performance.

2 Gait-relevant details

The configuration of Dante II is described in [2]. Some details of its design are relevant to the execution of gait. Specifically, the configuration of the actuated motions, computing resources, and available sensors influence the form of the gait controller we have devised.

2.1 Rappelling framewalker mechanism

Dante II is a framewalker; its 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 2. 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.

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.

Dante II has eleven actuated degrees-of-freedom (eight legs, stroke, turn, and tether) to be controlled, and that also need to be coordinated to regulate its posture (roll, pitch, and height).

2.2 Sensing terrain topography

Dante II senses the terrain topography with both perceptive imaging devices, and proprioceptive position and force sensors, annotated in Figure 2. From atop the mast, a conically-scanning, laser rangefinder can measure 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, and 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 positions of and forces on the eleven actuated motions, and posture of the body.

2.3 Computing and tethered telemetry

Dante II's missions require both supervisory and direct control. Its operator interface [3] allows automatic functions to be disabled and teleoperation to be enabled. The need for variable control modes motivated the selection of general-purpose computers and motion control boards.

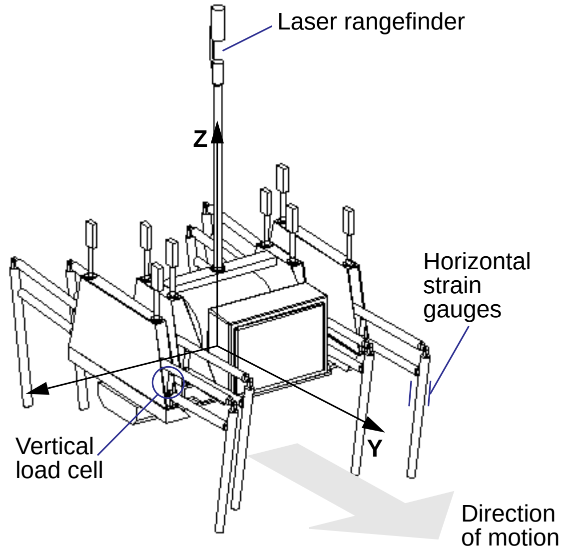

Figure 2: Dante II coordinates and sensors

The on-board computing hardware consists of three Motorola 68030 boards, one Sparc2 board (for perception processing), two Creonics motion control boards, a DAADIO board, and several custom PCBs (for power, brakes, etc.), all mounted in a VME backplane. Real-time control is distributed among the three 68030 processors, which all run the multi-tasking VxWorks operating system. The first processor collects sensor information, with filtering from the DAADIO, and writes state into shared memory at 120 Hz. The second processor drives eight leg servo-loops and services dedicated 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.

3 Gait execution design

We defined gait execution as the enabling of immediate actions to walk and to maintain safety and stability when confronted with unexpected events. It is constituted of its ability to stand, posture, step, and walk. Asynchronous control processes, *behaviors*, embody these abilities—they act independently to achieve or maintain desired states, and interact to walk. These behaviors are parameterized to allow external modification and direction, and form the basis of a hybrid planning/reacting architecture.

3.1 Specifying constituent abilities

We have tried to identify the basic abilities that will keep the robot safe and stable, and establish the structure of the fundamental walking cycle.

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 motion 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 **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.

3.2 Architectural considerations

We have been convinced, by our experiences 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.

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 [4] 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 [5] built a system based on such a neurological model and has demonstrated robust walking.

Both reactive and biological approaches possess properties necessary to gait execution: reaction to unexpected events, concurrency of reflexes, and coordination of actions. For Dante II, we also taken a behavioral approach to benefit from these properties, and have developed a network of behaviors to stand, posture, step, and walk. Our organization relates most directly to the control of the actuated degrees-of-freedom. (It also offers the possibility of changing the order of leg recovery and performing nonperiodic gaits but, of course, this cannot be demonstrated on a framewalker.)

Behavioral and biological architectures can entail some difficulty in interacting at a cognitive level to produce intentional behavior. Ethological evidence indicates a distinction between willed (intentional) behavior and automatic behavior.[6] We suggest a similar organization for controlling walking: planned actions to accommodate predictable occurrences, and automatic reactions for unpredictable events. Our approach, like other hybrid planning/reacting architectures (for example [7]), seeks to capitalize on the advantage of planning for anticipating productive actions, and on reacting for quickly accommodating disturbances in the desired goal state.

Connell [8] has suggested several ways, including parameterization, to guide behaviors. By organizing Dante II's behavioral gait controller around the actuated motions, action parameterization (like the height to raise the legs or the stroke to propel the body) is forgone. The sensitivity (for example, to contact forces, and to pitch and roll errors) can also be quantified and adjustable. By adjusting these parameters the human supervisor (or an independent planner) can guide the robot, directing its overall performance. This is the basis of Dante II's supervisory control interface.

3.3 Design of the gait control processes

We have implemented a gait controller with 24 asynchronous processes: eight *contact foot* behaviors to **stand**, eight *free foot* behaviors to **step**, one each of *raise legs, move frame* behaviors to **walk**, and *roll, pitch,* and *clearance* behaviors to **posture**. These behaviors are networked by binary links that carry inhibit and exhibit control signals. Each process has the same structure: it executes a nonterminating loop waiting for an incoming exhibit or inhibit signal. The inhibition/exhibition logic is simply, "exhibit when receiving one or more exhibit signals and no inhibit signals." When the process exhibits its behavior, it watches for signalled events and sensed conditions, and produces signals and actions.

The *contact foot* behavior (for each of the eight legs) 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 and lowering a foot, 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.

Conversely, the *free foot* behavior causes the foot to stay free, out-of-contact with the terrain. It is depicted in Figure 3; note that exhibition links terminate in an open circle and inhibition links in a closed, black circle. When

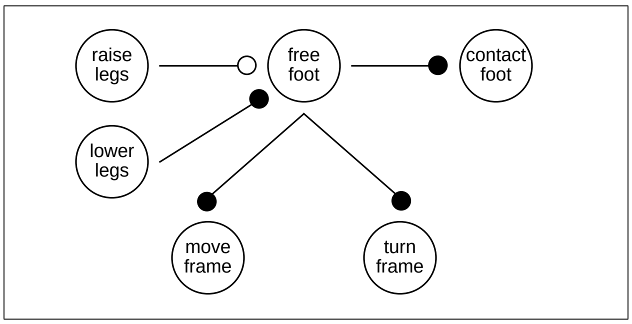

Figure 3: Free foot behavior

exhibited 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. Again, 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. Figure 4 shows the

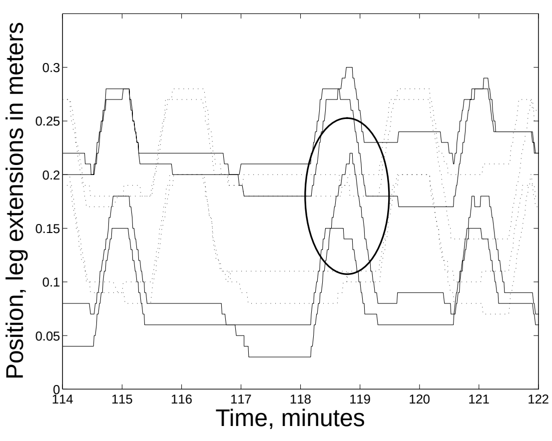

Figure 4: Leg bump during walking

extensions of all eight legs (inner frame legs are dotted) during a portion of the Mount Spurr descent. At minute 118.5, a raised leg has bumped the terrain and continued to raise up. The reaction time is less than 0.5 seconds.

Five behaviors: *raise legs, move* and *turn frame, lower legs,* and *sit still*, when sequenced together, enable walking. The *raise legs* behavior, shown in Figure 5, 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 *move frame* and *turn frame* behaviors. They then signal *lower legs*, which signals *sit still* (for image and data capture), and completing the cycle, *raise legs* again.

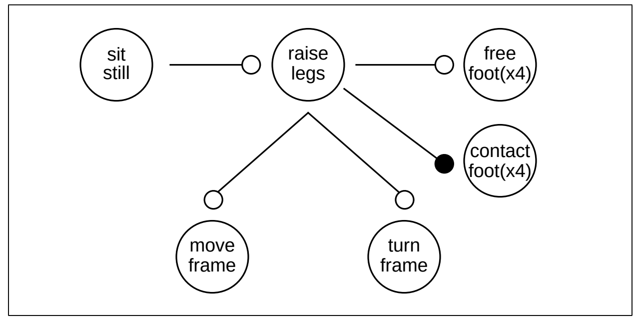

Figure 5: Raise pod behavior

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 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. In Figure 6, the body pitches at minute 110.0, and raises at 111.3 (both while advancing downhill). 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

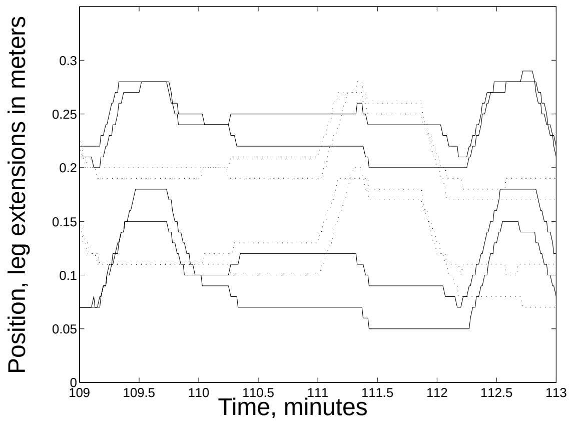

Figure 6: Pitch and raise while walking

not uncommon for Dante II to roll, pitch, and raise or lower (in any order) during the course of one body translation.

4 Gait performance

Dante II underwent two long duration tests (in Pittsburgh and Anchorage) before operating in Mount Spurr.

4.1 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 reaction occurred so quickly that body advance slowed almost imperceptibly.

In these tests we discovered how difficult and exhausting it is to teleoperate a walking robot. Autonomous walking is faster and, with fatigued operators, more reliable.

4.2 At an Anchorage gravel pit

The Anchorage gravel pit site is 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.

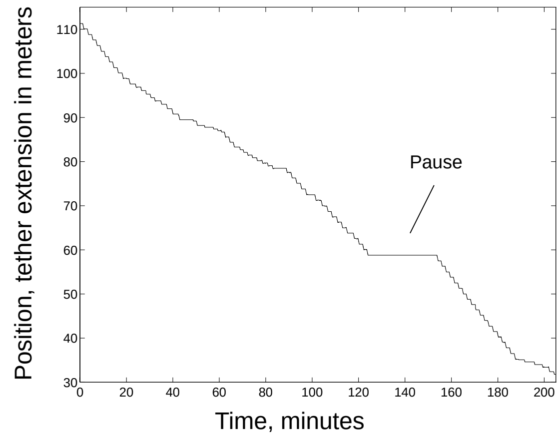

Figure 7: Autonomous ascent in gravel pit

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 is less than half the maximum speed dictated by the motor/amplifier configuration and is because of human delays in interpreting sensors, considering information, and making plans. When ascending the same terrain autonomously, it took 179 minutes (2:59), the gait controller averaged 0.51m/min, and in some areas averaging 0.67m/min, more than twice the human-controlled speed (shown after the pause in Figure 7).

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 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.

4.3 In Mount Spurr's crater

Mount Spurr was Dante II's final destination. It erupted three times in 1992 spreading 200 million cubic meters of ash over Alaska.[9] It is of interest because of its proximity to Anchorage and potential for further eruptions.

The 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 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.

On the upper slopes of the crater Dante II walked autonomously twice: 9.8m in 23.3 minutes (0.42m/min) and 9.6m in 19.78 minutes (0.49m/min). Shown in Figure 8, this is about twice the typical speed of teleoperation.

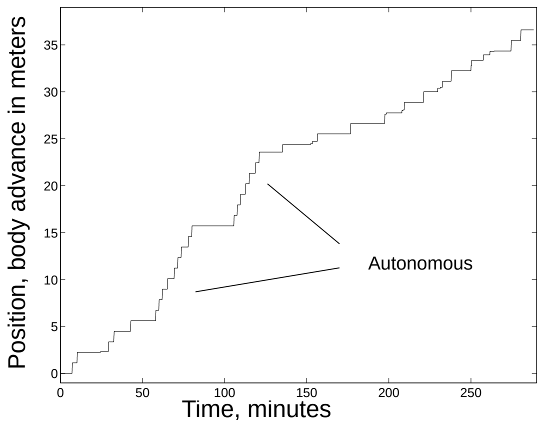

Figure 8: Autonomous walking on upper slopes

Because it was necessary to navigate across the chutes and ridges, Dante II experienced cross-slopes up to 30°. This severity was unexpected. We hoped to travel directly downslope as much as possible, but the robot reached dead ends that had taken hours or days to discover—apparently this is the nature of exploration. The most direct exits were to turn across the slope and climb over a ridge into the next chute. In Figure 1, Dante II was surmounting a small knob with extreme cross-slope to reach a fumarole.

Near the bottom of the descent, Dante II made two autonomous descends down a snow chute, 8.3m in 35.2 minutes (0.24m/min) and 6m in 12.3 minutes (0.49m/min). The snow was hard packed and rocks lying on its surface were easily cleared when bumped. The ascent from the crater was hampered by snow melt, mud, and freshly-exposed obstacles. Dante II was teleoperated during the entire ascent, about 100m, until it tipped on a 30° cross-slope and had to be rescued by airlift.

5 Conclusions

Gait generation, while unique to walking robots, is an instance of a broader issue in mobile robot control: the interaction of planning and execution. We have concluded that planning without adaptive execution is insufficient for walking in unstructured terrain because of unpredictable disturbances like bumps and slips. We have implemented a method of generating gait for a walking robot in which execution is performed by asynchronous gait control processes. These gait behaviors can be directed by specifying parameters that quantify their input sensitivity and output actions. Human operators can specify these parameters for the supervisory control of Dante II.

This is approach puts the fundamental ability to walk within the robot controller and minimizes sensing and communication, while still enabling robust and productive locomotion. During execution, actions are initiated directly by events, so reactions are quick and timely. In numerous tests behavioral gait execution has performed reliably. It has exceeded, in speed, the ability of a human to teleoperate the robot. Ultimately this autonomy may also prove more reliable than teleoperation because faster reaction aids survival.

6 Acknowledgments

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