Proceedings of the 1992 IEEE
International Conference on Robotics and Automation
Nice, France - May 1992

A Walking Prescription for Statically-Stable Walkers Based on Walker/Terrain Interaction

Peter V. Nagy[1], William L. Whittaker[1], and Subhas Desa[2]

[1]Field Robotics Center
The Robotics Institute
[2]Department of Mechanical Engineering
Carnegie Mellon University
Pittsburgh, PA 15213, USA

ABSTRACT

There is a need for walking robots to operate in natural, unknown terrain. The traversal of unknown terrain requires the characterization of walker/terrain interaction and its incorporation into a reliable walking control prescription. The walker/terrain interaction phenomena for the control of a statically-stable walking machine are described in this paper. The algorithms, measures, and knowledge of walker/terrain interaction phenomena are then combined to form a prescription for how to walk on general terrain. This prescription consists of two parts, nominal control and reactive control. The function of nominal control is the evaluation and execution of planned motions, based on predicted foot force redistributions, to achieve reliable locomotion. The function of reactive control is the monitoring of walker/terrain interaction in real-time to detect anomalous conditions and then responding with the appropriate reflexive actions. Simulations and experiments have been used to test and verify various aspects of the walking prescription.

1. INTRODUCTION

To date, most walking machines have walked on known, benign terrain. The techniques to implement walking on such terrain have relied on the integrity of the foot/terrain contact. However, there is a need for walking robots to operate in natural, unknown terrain, for example, to autonomously explore planets. The traversal of unknown terrain requires the investigation of the walker/terrain interaction and the subsequent development of a walking prescription based on the characterization of the interaction [1].

There is a growing recognition of the importance of accounting for the effects of natural terrain in walking control. For example, many recent works on servo level control of walkers focus on the effects of terrain compliance. Orin's force redistribution control method to minimize power consumption [2] has been supplanted by more efficient methods that emphasize the integrity of foot/terrain contact to avoid foot slippage [3],[4]. To further enhance the reliability of walker motions, the full interaction between the foot and terrain must be understood. However, the foot/terrain interaction (at any foot) is intimately related to the interactions of the other feet with the terrain. Therefore, we wish to address interaction phenomena of the entire walker with terrain.

The walker/terrain interaction phenomena for the control of a statically-stable walking machine are described in the next section. The algorithms, measures, and knowledge of walker/terrain interaction phenomena are then combined to form a prescription for how to walk on general, unknown terrain.

The walker/terrain interaction phenomena and the resulting prescription are broadly applicable to statically-stable walkers. However, methods and experiments are discussed in the context of AMBLER, a hexapod walking machine developed at Carnegie Mellon University [5],[6]. This walking robot was used extensively in the experimental portion of this work.

2. WALKER/TERRAIN INTERACTION

Interaction with the terrain occurs during the different elemental walking motions. The elemental walking motions are: altitude, attitude, leg positioning, propulsion, and force redistribution control. Altitude control of the robot does not significantly change the walker/terrain interaction. The method used to regulate body attitude will affect the nature of the interaction (Section 2.1). However, swinging a leg or propelling the body shifts the body c.g., and consequently causes some interaction to occur as detailed in Section 2.2. Every elemental walking motion will affect the stability of the robot. A method to quantify the stability while taking walker/terrain interaction into account is discussed in Section 2.3.

2.1 Attitude Control

The method by which the inclination of the walker is controlled affects the walker/terrain interaction. The conventional leveling method, which leads to an undesirable interaction, is described below. A different method which results in a more favorable interaction is then discussed.

The conventional attitude control method extends and retracts the vertical link of each leg by an amount, ΔZ_i, determined by using a small angle approximation:

$$\Delta Z_i = y_i \sin(\theta) - x_i \sin(\gamma) \qquad (1)$$

where: y_i is the horizontal distance of leg i to the pitch axis
x_i is the horizontal distance of leg i to the roll axis
θ and γ are the change in pitch and roll angles
ΔZ_i is the change in the height of leg i.

When changing the body attitude by this method, feet slip and/or there is a build-up of internal link forces. These effects are accentuated when the feet of the walker are at dissimilar elevations. Additionally, the body of the walker sways, mainly in the horizontal direction. Other leveling methods that also use only the vertical actuators but utilize more kinematic information have been derived and evaluated [7]. The resultant walker motions and terrain interaction for all of these methods are similar.

A different type of method was derived that uses all actuators to level the body. With this method, each new foot locations with respect to a fixed body coordinate frame are given by:

$$\hat{x}_2 = Rot(Y, -\gamma) Rot(X, -\theta) x_1$$

$$= \begin{bmatrix} \cos\gamma & \sin\theta\cos\gamma & -\cos\theta\sin\gamma \\ 0 & \cos\theta & \sin\theta \\ \sin\gamma & -\sin\theta\cos\gamma & \cos\theta\cos\gamma \end{bmatrix} x_1 \qquad (2)$$

where: x_1 is the current coordinate location of foot i

$\hat{x}_2$ is the new coordinate location of foot i

θ and γ are the change in pitch and roll angles

By using this method, an arbitrary point on the body (the fixed frame) may be kept from translating. More importantly, the use of all actuators to level the robot avoids foot slippage and build up of internal linkage forces due to flexure. However, this comes at the cost of greater power consumption, as all actuators are servoed. If the peak power consumption needs to be minimized, and the feet are at similar elevations, one of the methods that use only the vertical actuators to level the body should be used. On the other hand, when footfalls are at dissimilar elevations, the method that uses all actuators to level the body should always be used.

2.2 Vertical Force Redistribution

During body propulsion or leg swinging there is an active redistribution of the vertical contact forces exerted by the ground on the feet of the walker, even if the brakes are applied to the vertical actuators. When a walker has more than three legs in ground contact, the distribution of these vertical foot forces is indeterminate. It is desirable to be able to predict how these forces will redistribute due to a planned machine motion in order to assess the feasibility, reliability, and safety of planned walker motions. Additionally, the predicted foot forces should be compared to the actual forces during execution to determine the quality of the walker/terrain interaction.

Two methods were developed to predict how vertical forces redistribute due to c.g. motion. The *least-squares method* computes the force distribution after a planned motion by minimizing the second norm of the difference between the set of vertical foot forces before and after a proposed walker motion. A second method, the *compliance method*, utilizes leg/terrain compliance and kinematic constraints to determine the new force distribution. It can be shown that these two methods give exactly the same predictions when the compliance under each leg is equal [1]. A detailed description of these two methods, including all relevant assumptions is presented in [8]. The development and experimental verification of the compliance model are summarized below.

For a walker with n ground-contacting legs, $n > 3$, there are three applicable static equilibrium equations. The sum of the vertical forces equals the weight of the machine, and there are no net rolling or pitching moments. These constraints may be expressed mathematically as:

$$F_1 + F_2 + F_3 + \ldots + F_n = W \qquad (3)$$

$$X_1F_1 + X_2F_2 + X_3F_3 + \ldots + X_nF_n = X_cW \qquad (4)$$

$$Y_1F_1 + Y_2F_2 + Y_3F_3 + \ldots + Y_nF_n = Y_cW \qquad (5)$$

where: F_i is the vertical force on leg i

X_i, Y_i is the location of leg i

X_c, Y_c is the location of the center of mass

W is the weight of the walker.

Equations (3) - (5) are three equations in n unknowns. A further n - 3 equations are derived through kinematic constraints to yield n linearly independent equations. To derive these additional equations n - 3 sets of four legs are chosen. This is done systematically by choosing three ground-contacting legs as a reference tripod, and combining these with the remaining ground-contacting legs one at a time. With each of these sets of legs, the set of foot deflections corresponding to a force redistribution must be consistent with keeping all legs in ground contact [8]. Combining the resulting equation with Hooke's law for each compliant contact, each additional constraint equation is of the following form:

$$Y_{ix}F_i + m_{jx}F_j + m_{kx}F_k + m_xF_x = a_x \qquad (6)$$

where: legs i, j, and k form the reference tripod

leg x is the fourth leg under consideration

all m_i are a function of leg coordinates and spring compliances

a_x is a function of leg coordinates, spring compliances, and current foot forces.

A predicted negative foot force corresponds to foot lift-off, in which case the force on this foot is set to zero, and the forces on the remaining ground-contacting feet are recalculated.

To test the validity of the force prediction methods, experiments were carried out on the AMBLER. The body was propelled various distances, and the actual foot forces experienced by the AMBLER were compared to the values predicted by these methods. For example, the AMBLER was propelled forward (in the Y direction) by 1 meter on sand, as shown by the motion of the horizontal line in Figure 1.

The actual vertical foot forces measured on the AMBLER are shown in Figure 2(a) for the planned move depicted in Figure 1. The predictions from the compliance method for the same move are shown in Figure 2(b). The predictions are close enough to the actual forces resulting from executing the intended motion that the compliance method provides reliable vertical force predictions.

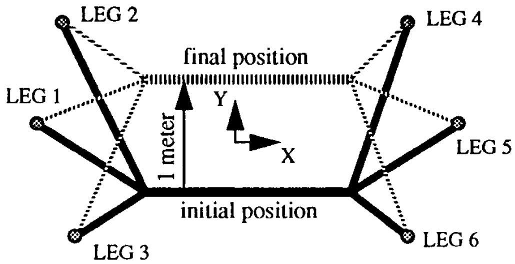

Figure 1. Propulsion Example.

The horizontal forces and moments were also monitored during the experiments with the AMBLER. These forces and moments did not vary in any predictable, systematic manner. The effect of these forces and moments on the redistribution of vertical forces was not significant.

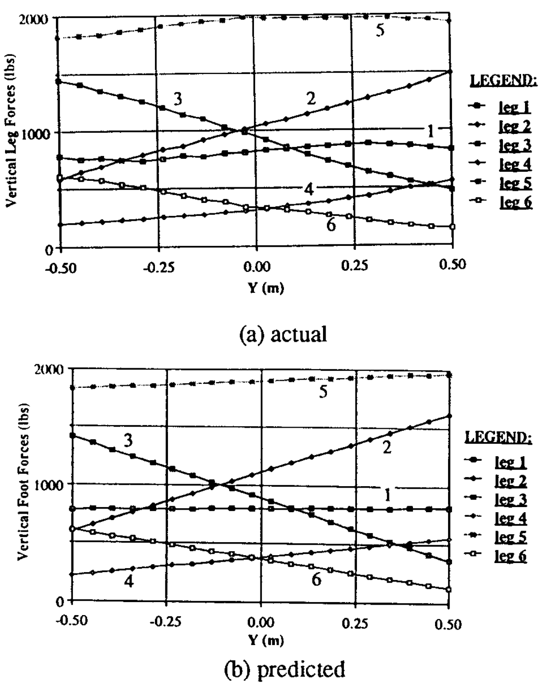

Figure 2. Vertical Force Redistribution Due to Body Motion.

2.3 Stability

A critical requirement for safe locomotion is that the stance of a walker should be stable. To ensure reliable locomotion this stability should be quantified. The resulting stability measure should be used in the planning of walker motions, such that the planned motions do not unduly jeopardize the safety of the robot. The measure of stability should also be monitored by the real-time controller during the planned motion to safeguard the robot. Previous stability measures are briefly discussed, and a new stability measure is introduced which takes into account the effects of compliant terrain.

A walker is said to be stable if the vertical projection of its c.g. onto a horizontal plane lies inside the polygon formed by the vertical projections of the feet on the same plane. An example of the support polygon for five-legged ground contact is shown in Figure 3. For the walker to remain stable, the projection of its c.g. must lie inside this polygon. For more conservative (safer) walking, the vertical projection of the c.g. may be constrained to move in the *Conservative Support Polygon* (CSP), which is a subset of the support polygon [9]. If the motion of the c.g. is confined to this smaller area, the machine remains stable even if the support of any one leg fails. The planning algorithms used on the AMBLER constrain the projection of the body c.g. to lie within the CSP.

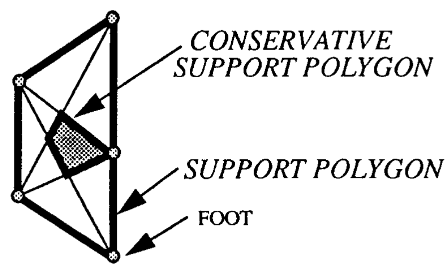

Figure 3. Plan View of the Support Polygons for Five Ground-Contacting Feet.

To quantify the stability, the distance of the c.g. projection to the boundary of either support polygon may be used. However, a better measure is the *Energy Stability Margin* (ESM) developed by Messuri and Klein [10]. This measure calculates the minimum energy required to tip over the walker. The ESM is found by first calculating the energy to tip the c.g. over each pair of adjacent legs of the support polygon. The relevant geometry for calculating the "tipover energy" for a pair of feet is shown in Figure 4. To tip the walker over these two feet, the c.g. has to rise by the height h to reach incipient tipover, requiring energy mgh, where m is the mass of the walker, and g is the force of gravity. The ESM of the machine is the smallest energy stability resulting from the calculations involving each pair of legs. The analytical determination of the ESM has been derived in [1].

The ESM is better than previous stability measures since it quantifies the energy of a disturbance (such as a support failure) that is required to topple the robot. However, it does not take into account the compliant effects of natural terrain. We have augmented the ESM by taking leg and terrain compliance into account in the development of the *Compliant Energy Stability Margin* (CESM). When tipping over a pair of feet the load on these feet increases, as they bear the full weight of the walker. If these feet have compliant contacts, they will sink as a result of the increased loading. Therefore, the c.g. does not rise as much as in the ESM analysis to reach incipient tipover.

To calculate the Compliant Energy Stability Margin, the ESM for each edge of the support polygon is first calculated. The geometry of incipient tipover is shown in Figure 5. The ESM calculates the energy required for the c.g. to reach point j. With compliant footfalls the feet sink by Δz_1 and Δz_2 due to increased loading. As a result, the c.g. rises by a smaller amount, to point k, in this example. Therefore the CESM predicts smaller energy stability.

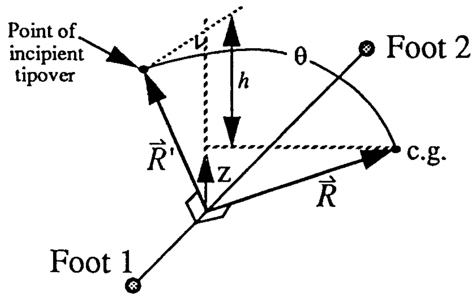

Figure 4. Tipover Geometry.

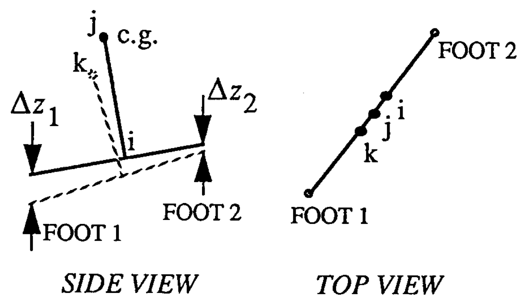

Figure 5. Incipient Tipover for Rigid and Compliant Terrain.

The ESM and CESM measures for the same 1 meter propulsion example discussed in Section 2.2 are shown in Figures 6 and 7 for the case of the walker on flat and sloped sandy terrain, respectively. In the former case, the CESM is only slightly smaller than the ESM throughout the walker motion. With the walker on a 30 °slope of sand, the CESM is approximately 13 to 15% less than the ESM. The reason for the significant difference between the two stability margins for the sloped terrain is that the sloped terrain contacts have higher effective vertical compliance.

It is worth noting that with the flat ground case, the stability is a maximum near the middle of the trajectory. With the machine propelling forward horizontally while ascending the slope, the stance stability is a maximum at the end of the trajectory due to the machine geometry.

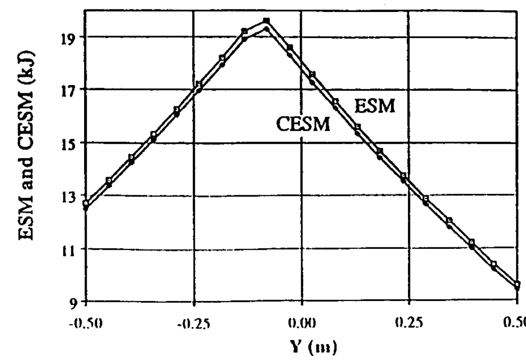

Figure 6. ESM and CESM for the Propulsion Example.

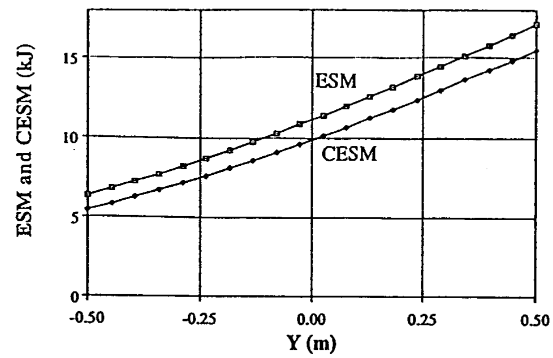

Figure 7. ESM and CESM for Propulsion on a 30° Slope.

3. A PRESCRIPTION FOR WALKING

To walk on unknown terrain (e.g., unstructured, planetary terrain), the method chosen should be conservative in order to ensure reliable locomotion. A prescription for walking has been developed based on our knowledge of walker/terrain interaction. The prescription consists of two parts: nominal control and reactive control. Nominal control is normally used as the walker progresses, while reactive control is a real-time safety monitor that preempts nominal control in response to anomalous conditions.

3.1 Nominal Control

In the control simulations (using a dynamic model which included non-linear, non-conservative, foot/terrain interaction models [11]) it was observed that simple position and velocity motion control sufficed in achieving stable and accurate motion [12]. Consequently, motion control boards were procured for the AMBLER; over several thousands of hours of operation they have proved robust for implementation of both nominal and reactive control.

The elements of nominal walking are: altitude, attitude, propulsion, stepping, and force redistribution control. For a gravity-decoupled robot, it is possible to decouple most of the elemental walking motions into motions that use either vertical or horizontal actuations. Peak power consumption may be significantly reduced by carrying out motions that require horizontal and vertical actuations sequentially.

For conservative walking, the walker steps one leg at a time. A gait cycle refers to the sequence of motions associated with a single step. A walking cycle consists of a sequence of gait cycles, one (gait cycle) for each leg of the walker. A prescription for nominal control of a gait cycle, shown in Figure 8., has been developed based on the elements of walker/terrain interaction discussed in Section 2. An intended set of walker motions that comprise the gait cycle (body propulsion and repositioning of a stepping leg) are planned by the gait planner. The effect of these planned motions on the walker/terrain interaction is evaluated by the nominal walking controller. If the gait cycle motions may be reliably carried out they are executed, otherwise, the stance of the robot needs to be adjusted. The operation of the proposed nominal controller is detailed below.

At the beginning of the gait cycle, the walker is in a stable stance, and positioned to start the new cycle. Before the planned cycle is executed, the foot forces that result from the planned motion are predicted and assessed to determine the viability of the intended gait cycle. The integrity of the foot/terrain contact is of utmost importance for those feet that have large forces on them. Therefore, the nature of each foot/terrain contact is evaluated. A region of the foot which the resultant of the vertical contact forces exerted by the ground on the foot should pass through for stable ground contact. If the resultant force (obtained from a six-axis force sensor) does not lie within this region, the foothold is characterized as a "toe-hold." A large force at a toe-hold is undesirable as such contacts are more likely to result in foot slippage. Therefore, if toe-holds exist, the vertical force distribution predictions are required to ensure that the forces at feet contacts which are toe-holds do not exceed some threshold value.

Given a walker stance and a set of intended walker motions the resultant vertical foot forces are predicted. The terrain contacts are evaluated to determine if there are toe-holds. If there are no toe-holds, execution of the walking cycle proceeds as shown in (the right hand side of) Figure 8. Even with toe-holds, if the planned motions result in predicted acceptable foot forces, the walking cycle proceeds. Otherwise, a new vertical force distribution is selected for the given stance of the walker. The new distribution should be chosen such that it is likely to lead to an acceptable set of foot forces during the planned walker motions. If the resulting force redistribution is acceptable in this instance, then the foot forces necessary to achieve this distribution are obtained by executing small motions of the vertical linkages. If a feasible foot force distribution to achieve the desired motions cannot be realized, then the intended gait cycle is not executed. In this case, the gait planner should plan a new gait cycle.

With a favorable predicted walker/terrain interaction, an appropriate sequence of intended walker motions are carried out. First the body attitude (tilt) is regulated, by the appropriate leveling method of those described in Section 2.1, to bring it into its acceptable range. Next, the body altitude is regulated to the desired height. Having performed these control actions, the vertical actuators are "locked out" (braked), and the body is propelled horizontally. This is followed by taking a step, which consists of lifting a foot, swinging it, and placing it in a new foothold location. The new foothold is evaluated for its stability for subsequent walker motions. For example, the evaluation criteria may include the ability of the foothold to sustain large vertical forces based on pre-loading the foot, or detection of toe-hold. If the new foothold is acceptable, the next planned gait cycle may proceed. Otherwise, the gait planner chooses a new foothold location and determines the corresponding leg motions to realize the new foothold.

An underlying assumption in the nominal control prescription presented here is that the prediction of stance stability of the intended walker motions is evaluated at the gait planner level. Alternatively, the nominal walking controller could assess the stability of the planned motions.

3.2 Reactive Control

The nominal walking control prescription evaluates the walker/terrain interaction as a basis for choosing control actions to increase the probability of achieving safe and reliable locomotion. The nominal walking cycle is intended to be the principal mode of operation of the walker. However, since the walker is operating on unknown terrain, it is bound to encounter unforeseen real-time conditions which demand a reflexive, reactive control mode to respond appropriately.

With reactive control, the walker/terrain interaction and the state of the machine are continuously monitored as shown in Figure 9. For slowly moving, statically-stable walkers, such as the AMBLER, it is sufficient to simply halt the robot for the majority of unexpected events. However, there is a dynamic failure mode that is of great concern: tipover of the walker. This may occur due to a support failure, i.e., a weakening of stance caused by the sudden loss of the ability of the terrain to support the foot. The reactive leveling algorithm (described in the next sub-section) was developed for the walker to respond to such an event. This algorithm is designed to bring the body close to level. When the walker and terrain have stabilized, the walker is halted. A new, favorable stance is then established, and nominal walking may then continue.

Static failure events include unexpected foot forces, violating an allowable stability threshold, and machine failures, such as amp faults, processor faults, motion controller faults and sensor faults. All of these failure modes should be monitored in real time to achieve reliable walking. The foot forces may be monitored in real time, and compared to their predicted values (using the method described in Section 2.2) in order to determine if the walker/terrain interaction is anomalous, in which case the machine can be brought to a halt, and a new, stable stance established. The stability of the machine should also be monitored in real-time using the method described in Section 2.3 in order to stop motion if some anomalous walker/terrain interaction lessens the machine's stability.

3.2.1 Reactive Leveling

Slowly-moving statically-stabilized walking machines are in danger of tipping over when support failure(s) occur. The function of the reactive leveling algorithm is to provide the appropriate corrective response to these support failures. The response is formulated without knowledge of which supports failed. The reactive leveling algorithm is depicted in Figure 10.

Reactive leveling incorporates tilt sensing within the control loop. Given the current roll and pitch of the machine, the vertical leg extensions required to level the machine are calculated, assuming that the legs are in ground contact. The ratio of the required extensions between legs serves as the ratio of velocity commands that are sent to each leg whose foot is in ground contact. For small values of tilt, the leg velocities are set to zero, so that the machine does not "hunt" about the level position.

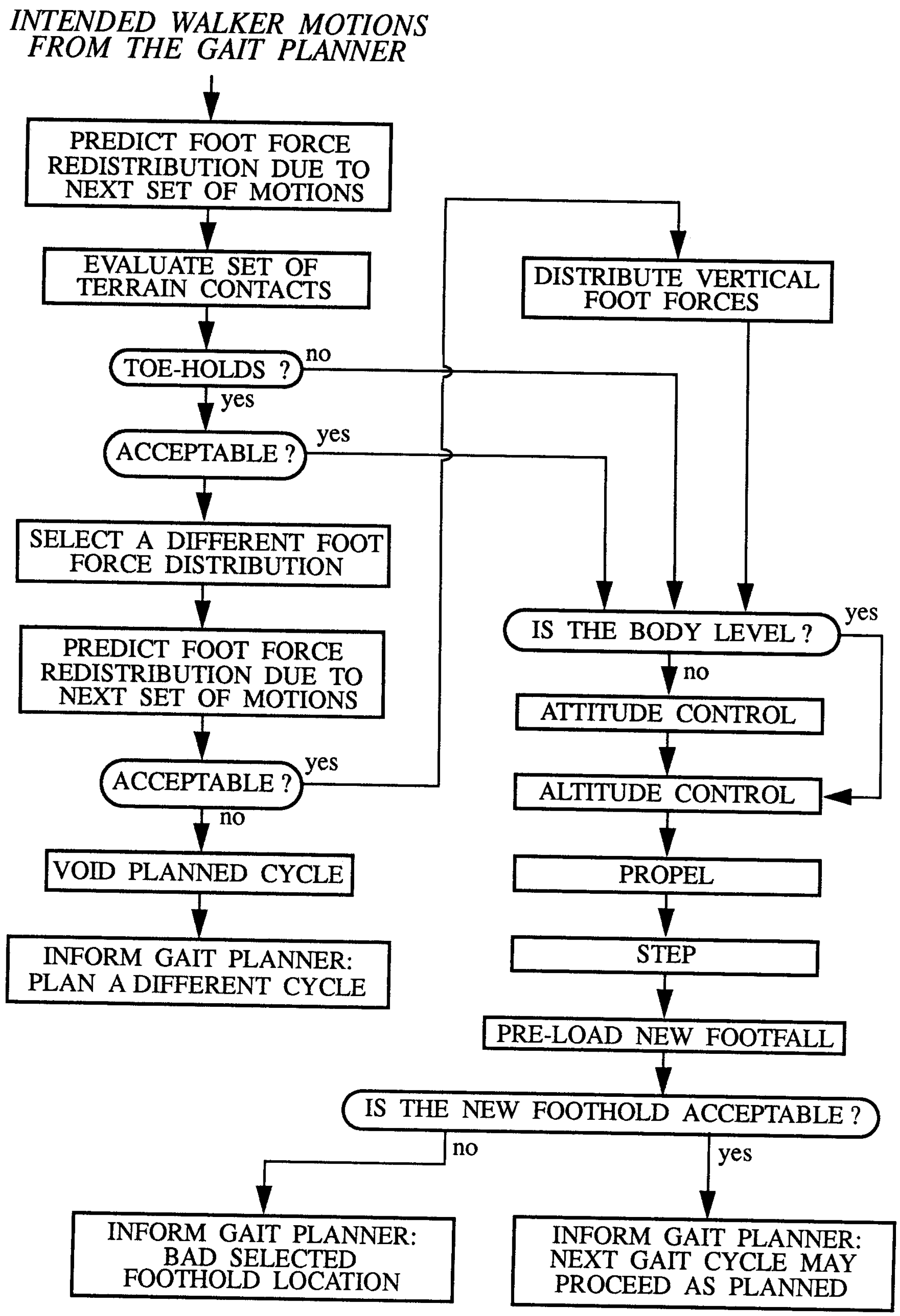

Figure 8. Nominal Control Prescription for Walking on Unknown Terrain.

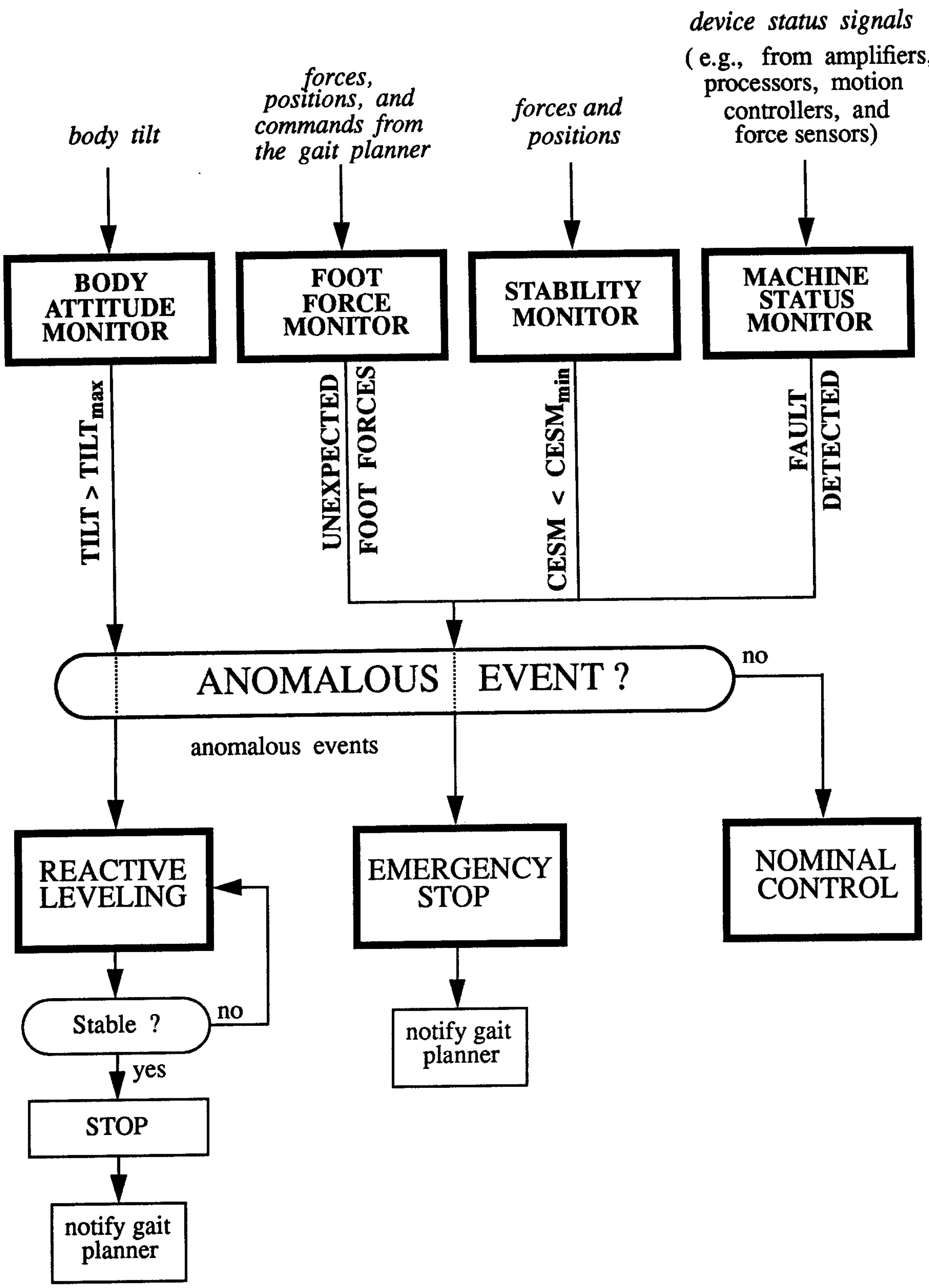

Figure 9. Prescription for Walking on Unknown Terrain.

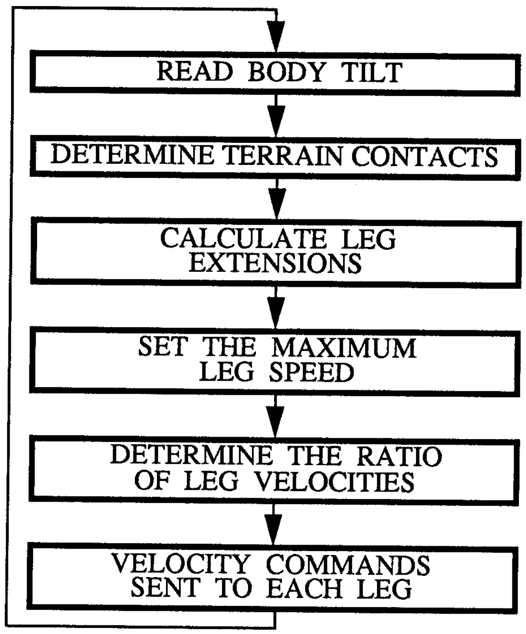

Figure 10. The Reactive Leveling Algorithm.

If the reactive levelling algorithm commanded leg velocities to all legs as determined by the extension ratios, the walker will still come to level. However, legs that are in the air as a result of the support failure(s) will not make ground contact if the reactive levelling maneuver is done in that manner. Moreover, these legs usually further retract such that they do not contribute to the machine's stability. To achieve a levelling recovery that is more stable, legs with feet that are in the air extend slowly, until they contact the ground. After having made contact, they join the subset of legs that are participating in the reactive leveling algorithm.

4. CONCLUSIONS

For the reliable locomotion of walking robots it is crucial to take into account walker/terrain interaction. Therefore, in the first half of the paper, the important elements of walker/terrain interaction were characterized and quantified. These walker/terrain interaction elements are used to form the basis for the development of the walking prescription (shown in Figure 9. This prescription consists of two parts, nominal control and reactive control. The function of the nominal control prescription is the evaluation and execution of planned motions, based on predicted foot force redistributions, to achieve reliable locomotion. The function of the reactive control prescription is monitoring the walker/terrain interaction in real-time to detect anomalous conditions and then responding with the appropriate reflexive actions. Simulations and experiments have been used to test and verify various aspects of the walking prescription.

Complete implementation and refinement of the walking prescription is an important area for future research. To this end, further work needs to be done in the following areas: the characterization of foot/terrain contacts, criteria for determining acceptable foot force distributions, and criteria to guide the selection of vertical foot forces for subsequent motions.

ACKNOWLEDGMENTS

The authors acknowledge the financial support provided by NASA under Grant NAGW 1175. The authors also acknowledge other members of the CMU Planetary Rover Group and the Field Robotics Center who provided assistance during various stages of the work.

REFERENCES

[1] P.V. Nagy, An Investigation of Walker/Terrain Interaction, Ph.D. Thesis, Dept. of Mechanical Engineering, Carnegie Mellon University, Pittsburgh, PA, August 1991.

[2] D.E. Orin, Interactive Control of a Six-Legged Vehicle With Optimization of Both Stability and Energy, Ph.D. Thesis, Ohio State University, 1985.

[3] C.A. Klein and Kittivatcharapong, "Optimal Force Distribution for the Legs of a Walking Machine with Friction Cone Constraints," IEEE Journal of Robotics and Automation, Vol. RA-6, No. 1, Feb. 1990, pp. 73-85.

[4] V. Kumar and K.J. Waldron, "Force Distribution in Walking Vehicles," ASME Journal of Mechanical Design, Vol. 112, March 1990, pp. 90-99.

[5] J. Bares and W. L. Whittaker, "Configuration of an Autonomous Robot for Mars Exploration," Proc. 1989 World Conference on Robotics Research: The next five years and Beyond, Gaithersburg, MD, May 7-11, 1989, pp. 1:37-1:52.

[6] J. Bares and W. L. Whittaker, "Walking Robot with a Circulating Gait," Proc. IEEE International Workshop on Intelligent Robots and Systems, Tsuchiura, Japan, July 1990, pp. 809-818.

[7] Gonzalez de Santos, P.V. Nagy, and W.L. Whittaker, "Leveling of the AMBLER Walking Machine: A Comparison of Methods," CMU Robotics Institute Technical Report CMU-RI-TR-91-13, July 1991.

[8] P.V. Nagy, S. Desa, and W.L. Whittaker, "Predicting Force Redistributions on Walking Robots for Reliable Locomotion: Modeling and Experiments," submitted to the 1992 ASME Mechanisms Conference, Phoenix, AZ, Sept. 13-16, 1992.

[9] S. Mahalingham and W.L. Whittaker, "Terrain Adaptive Gaits for Walkers With Completely Overlapping Leg Workspaces," Proc. of Robots 13, Gaithersburg, MD, May 7-11, 1989, pp. 6:1-6:14, reprinted as SME Technical Paper MS89-298.

[10] D.A. Messuri and C.A. Klein, "Automatic Body Regulation for Maintaining Stability of a Legged Vehicle During Rough Terrain Locomotion," IEEE Journal of Robotics and Automation, Vol. RA-1, No. 3, Sept. 1985, pp. 132-141.

[11] D.J. Manko, A Model of Legged Locomotion on Natural Terrain, Ph.D. Thesis, Dept. of Civil Engineering, Carnegie Mellon University, Pittsburgh, PA, April 1990.

[12] P.V. Nagy, et. al., "Simulation of Postural Control for a Walking Robot," Proc. of IEEE Int. Conf. Systems Engineering, Dayton, OH, Aug 1-3, 1991, pp. 324-329.