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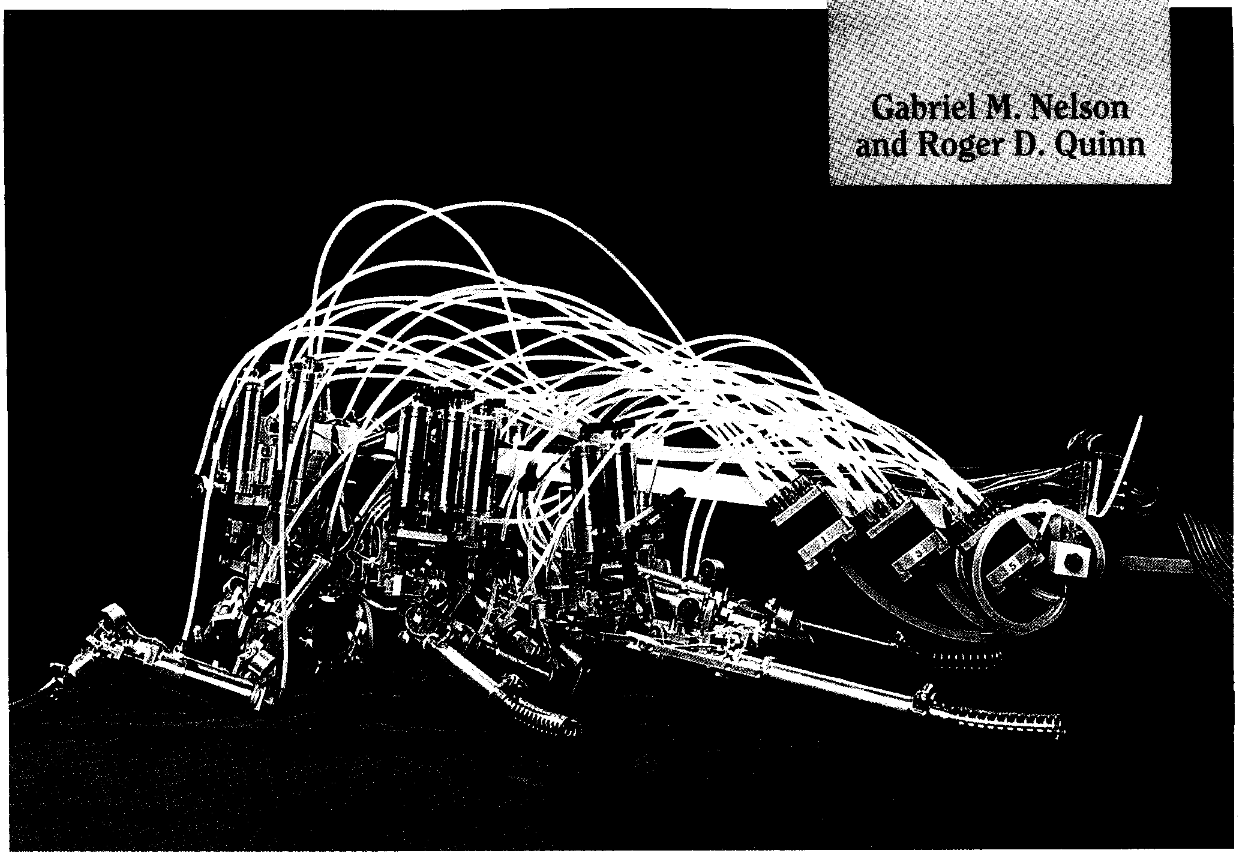

Fig. 1. Robot III, a cockroach-like robot.

POSTURE CONTROL of a *Cockroach-like Robot*

As legged robots become more animal-like, it is likely that these robots will have many complex limbs with redundant degrees of freedom (DOF). This is especially true when we desire them to move like an animal. Animals are capable of spontaneous and non-stereotyped locomotion, such as turning, swaying, twisting, deliberately falling, jumping, climbing, and running. Therefore, it becomes difficult to provide joint space trajectories, in real-time, for these complex movements when many limbs are simultaneously involved, and when some or all of these limbs contain redundant DOF. When locomotion takes place rapidly, it has been suggested that there is a feedforward control component that involves a proactive, higher level computation in the nervous system [1]. In this paper, we suggest and demonstrate an intuitive and computationally simple algorithm for controlling the posture of a complex, multileg robot with many redundant DOF. The algorithm avoids inverse kinematics by issuing feedforward force commands to both maintain static posture and generate body motion. In so doing, it is also shown that the multileg mechanics of postural control can be reduced to a simple center-of-pressure representation, or equivalently, an instantaneous virtual leg model.

A previous Bio-Robotics Laboratory robot, Robot II [2], was inspired by the stick insect and had three degrees of freedom in each of its six legs. It was built as part of the ongoing Bio-

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Robotics program [3] at Case Western Reserve University. Joints were driven by DC motors using proportional position control with variable gains. The robot could walk in a continuum of insect-like gaits and traverse irregular terrain using an insect-based distributed controller. Posture control was achieved by a mixture of processes local to joints and legs, and two global algorithms. The first global algorithm compared an individual leg load to the average across all legs, and incremented the desired foot position to help equalize load among legs. The second monitored body orientation by averaging shoulder positions and adjusting desired foot setpoints to conform the body to overall terrain orientation.

Robot III [4], [5] is a hexapod robot modeled after the *Blaberus* cockroach (see Fig. 1). The robot has an overall body length of 30 inches, which is 17 times larger than the animal. The total weight of the robot is 30 pounds. Three, four, and five DOF in each rear, middle, and front leg, respectively, enable propulsion, lifting and turning, and sensory functions [6]. These 24 DOF are actuated using 36 off-the-shelf, double-acting pneumatic cylinders [7]. Each joint uses a pair of three-way solenoid valves driven with 50 Hertz pulse-width-modulation. Single-turn potentiometers provide angle feedback at each joint. 100 psi air is supplied to the valve blocks at the rear of the abdomen. The force output of the cylinders can be approximated by a sigmoidal function of the duty cycle, with piston-face area and supply pressure parameters.

Posture Controller

Posture control is the active and continuous maintenance of body stability in all regimes of locomotion. These regimes include standing, walking, and running. In ongoing research in physiology, wherein researchers are seeking to understand how control responsibility for posture and locomotion is distributed throughout the nervous system, one aspect that is clear is the importance of higher centers of the nervous system for normal posture. This suggests that posture control is more than local reflex interaction. It is the orchestration and tuning of these reflexes according to some central desired behavior. Horak and Macpherson write in the Handbook of Physiology [8],

> *Posture is no longer considered simply as the summation of static reflexes but, rather, the complex interaction of sensorimotor processes and internal representations of those processes. Postural orientation involves active control of joint stiffnesses and such global variables as trunk and head alignment, based on the interpretation of convergent sensory information. Postural equilibrium involves coordination of efficient sensorimotor strategies to control the many degrees of freedom for stabilization of the body's center of mass during either unexpected or voluntary disturbances of stability.*

Although investigated in different contexts and by various researchers, the approach to posture control for Robot III was inspired by the Virtual Model control scheme as presented by Pratt, et al. [9]. Contributing research fields are also described well by Pratt [10]. A description of this scheme is discussed in the following sections. Quinn and Lin [11] used the inverse of this approach in a dynamic simulation of Robot II. This paper proposes an internal model tailored to the locomotion needs of a system such as Robot III. The concepts represented by this model are by no means new [12], [13], but one goal of this work is to demonstrate the successful implementation of these ideas into a complex, animal-like robot.

Single Leg Mechanics

Here we consider what contribution a single limb has on force production at the body of the robot. The system consists of the main body with its own fixed reference frame (1-frame), and a sequential numbering of leg segments out to the foot, each with its own body-fixed reference frame (2-, 3-, etc. frames). The body reference frame can be located at (but is not restricted to) what can be considered an average center of mass (CM) position. (This is a static position. It does not require a calculation of instantaneous CM location.) The segments are connected with rotary joints only.

In this application, we assume that the leg maintains a point contact with the ground, producing an "unactuated ankle" constraint. This generates a required relationship between the forces and moments applied by the leg, ℓ, on the body,

$$\underset{\sim}{M}_{\ell} = \tilde{W}_{1\ell}\, C_{1N}\, \underset{\sim}{F}_{\ell} = \bar{J}_{\ell}\, \underset{\sim}{F}_{\ell}, \quad \ell = i, ii, \ldots, \mathrm{L}, \tag{1}$$

where $\underset{\sim}{F}_{\ell}$ and $\underset{\sim}{M}_{\ell}$ are force and moment vectors, respectively, applied at the body's reference frame. L represents the number of legs in contact with the ground at this time. $\underset{\sim}{F}_{\ell}$ is expressed with respect to an inertial reference frame (N-frame) while $\underset{\sim}{M}_{\ell}$ is expressed with respect to the body (1-frame). $\underset{\sim}{W}_{1\ell}$ is the position of the foot of leg ℓ in the body's reference frame, and $\tilde{W}_{1\ell}$ represents a skew operation on this vector,

$$\tilde{W} = \begin{bmatrix} 0 & -W_z & W_y \\ W_z & 0 & -W_x \\ -W_y & W_x & 0 \end{bmatrix}. \tag{2}$$

C_{1N} is a 3x3 rotational transformation matrix from the inertial frame to the body frame. A recursive set of $\underset{\sim}{W}$ vectors for a leg with two segments can be expressed as follows:

$$\begin{aligned} \underset{\sim}{W}_1 &= \underset{\sim}{L}_1 + C_{12}\underset{\sim}{W}_2, \\ \underset{\sim}{W}_2 &= \underset{\sim}{L}_2 + C_{23}\underset{\sim}{W}_3, \\ \underset{\sim}{W}_3 &= \underset{\sim}{L}_3, \end{aligned} \tag{3}$$

where each vector $\underset{\sim}{L}_i$ represents the position of the next distal (i+1) body-fixed reference frame in the i-frame (typically located at the next joint), each vector being expressed with respect to the i-frame (see Fig. 2). Thus, the transpose Jacobian for a given leg with m–1 segments is expressed as

$$J^T = D^T \begin{bmatrix} \tilde{W}_2^T C_{2N} \\ \tilde{W}_3^T C_{3N} \\ \vdots \\ \tilde{W}_m^T C_{mN} \end{bmatrix}, \tag{4}$$

where D is a matrix describing the specific joint geometries [14].

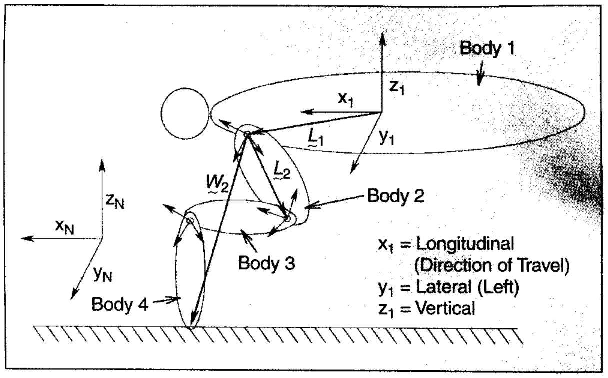

Fig. 2. Single leg notation.

Somatosensory Feedback of Body Position

Somatosensory feedback has its origin outside special sense organs, such as are found in visual or vestibular systems. It comes from interaction of the body with the environment. For both robustness and simplicity, Robot III (and Robot II [2]) does not rely on any single sensory device for determining body position. Unlike other robots with fewer legs, it is possible to estimate this information from the three or more simultaneous stance legs.

Using a least squares approximation, a support surface plane is estimated from the positions of the stance feet. This calculation produces an estimate for C_{1N} which excludes any yaw component. The height of the robot is estimated by averaging the opposite of the vertical (z) locations of the feet. Determining a yaw angle, as well as the horizontal (x and y) location of the body requires a convention, since somatosensory data will contain no absolute information about the orientation of the body relative to the ground along these axes. This is further complicated when legs are not in stance. Preliminary results indicate that it is sufficient to simply average the x, y, and yaw locations of all the feet, regardless of state, to arrive at a suitable reflection of body location. Sensing the orientation of gravity is external to this calculation. It would involve the use of an inclinometer and/or force data. Cockroaches, having no single sensor for detecting gravity, appear to use convergent force data from the exoskeleton. For the sake of this discussion, we will assume that gravity acts solely in the vertical, negative z direction.

Multileg Mechanics

All stance legs act on the body of the robot in parallel. Considering an arbitrary case in which four legs (L = 4) are in stance we have,

$$\begin{bmatrix} I & I & I & I \\ \bar{J}_i & \bar{J}_{ii} & \bar{J}_{iii} & \bar{J}_{iv} \end{bmatrix} \begin{bmatrix} \underset{\sim}{F}_i \\ \underset{\sim}{F}_{ii} \\ \underset{\sim}{F}_{iii} \\ \underset{\sim}{F}_{iv} \end{bmatrix} = \begin{bmatrix} \underset{\sim}{F} \\ \underset{\sim}{M} \end{bmatrix}, \tag{5}$$

$$\underset{\sim}{F}^T = [F_x \; F_y \; F_z],$$

$$\underset{\sim}{M}^T = [M_x \; M_y \; M_z],$$

where $\underset{\sim}{F}$ and $\underset{\sim}{M}$ (no subscript) represent the combined action of all stance legs on the body. I is the identity matrix. The goal is to specify virtual forces, $\underset{\sim}{F}$ and $\underset{\sim}{M}$, using an appropriate and capable virtual model (hence the name "Virtual Model"), and then to solve for the individual leg forces, $\underset{\sim}{F}_\ell$, that would tend to produce these virtual forces. This is not a trivial problem, and has received much attention in several decades of research. To specify $\underset{\sim}{F}$ and $\underset{\sim}{M}$, we could simply drive the position of the body using imaginary actuators (of our choice) following desired behaviors. In controlling a planar biped robot, Pratt, et al., used intuitive actuators such as the "dog-track bunny," a linear damper to control speed, and a "granny walker," a spring arrangement to control body height and attitude [9]. Choosing these model actuators is beautifully open-ended, yet is limited by, among other things, the amount and quality of sensory information available to the robot.

Solving the Force Distribution Problem

At least three methods have been used to solve the redundancy problem presented by (5). The first method entails using additional constraints to create a square and (hopefully) invertible coefficient matrix to immediately solve for the local leg forces. The second involves pseudoinverses that provide some desirable qualities (such as preservation of configuration after a cycle of motion [15]). Related to this, the third method involves using optimization functions that portray some desirable behavior (i.e., minimize joint torques or force distribution [16], base reactions [17], joint motions, kinetic energy). Optimization has been used for the control of redundant manipulators for many years [18], [19].

The approach taken in this paper borrows from the third of these techniques. The additional constraint method was investigated, but generally suffered from singularities which depended on the kinematic state of the system. The foremost of these singularities, which is discussed below, can be used to significantly simplify the force distribution problem and introduce an intuitive center-of-pressure representation. This, in turn, allows the stance mechanics to be divided into vertical and horizontal optimization problems. The resulting algorithm is consistent regardless of the number of legs simultaneously contacting the ground.

We begin by introducing some dimensionless parameters. Let each leg, ℓ, assume a vertical load responsibility coefficient n_ℓ,

$$n_\ell = \frac{F_{z\ell}}{F_z}, \quad \sum_\ell n_\ell = 1, \quad \ell = i, ii, iii, iv. \tag{6}$$

Also, let the direction in which each leg pushes be described by two other dimensionless coefficients,

$$c_{x\ell} = \frac{F_{x\ell}}{F_{z\ell}}, \quad c_{y\ell} = \frac{F_{y\ell}}{F_{z\ell}}. \tag{7}$$

Eq. (5), reduced from six to five rows by the introduction of (6), can be expressed in terms of these coefficients,

$$\begin{bmatrix} n_i & 0 & n_{ii} & 0 & n_{iii} & 0 & n_{iv} & 0 \\ 0 & n_i & 0 & n_{ii} & 0 & n_{iii} & 0 & n_{iv} \\ & & & & & & & \\ \bar{n}_i^1 & \bar{n}_i^2 & \bar{n}_{ii}^1 & \bar{n}_{ii}^2 & \bar{n}_{iii}^1 & \bar{n}_{iii}^2 & \bar{n}_{iv}^1 & \bar{n}_{iv}^2 \\ & & & & & & & \end{bmatrix} \begin{bmatrix} c_{xi} \\ c_{yi} \\ c_{xii} \\ c_{yii} \\ c_{xiii} \\ c_{yiii} \\ c_{xiv} \\ c_{yiv} \end{bmatrix} = \underset{\sim}{\bar{F}}, \tag{8}$$

where

$$\bar{n}_i^k = n_i \bar{J}_i^k, \quad \bar{J}_i^k \equiv k^{th} \text{ column of } \bar{J}_i \tag{9}$$

and

$$\underset{\sim}{\bar{F}} = \begin{bmatrix} \bar{F}_1 \\ \bar{F}_2 \\ \bar{F}_3 \\ \bar{F}_4 \\ \bar{F}_5 \end{bmatrix} = \frac{1}{F_z} \begin{bmatrix} F_x \\ F_y \\ M_z \\ M_y \\ M_z \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ \\ \bar{n}_i^3 + \bar{n}_{ii}^3 + \bar{n}_{iii}^3 + \bar{n}_{iv}^3 \\ \\ \end{bmatrix}. \tag{10}$$

The characteristics of the five equations in (8) prove useful for simplifying this problem. Denoting the position of the foot relative to the body, expressed with respect to the N-frame, as

$$\underset{\sim}{p}_{ifoot} = \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} = C_{N1} \underset{\sim}{W}_{1i}, \tag{11}$$

we can consider a case in which the body of the robot is coincident with the N-frame ($C_{1N} = I$; in the Appendix, we show that this assumption is inconsequential), and all of the stance feet are at equal vertical (z_i) locations (such as standing on a flat surface). This causes the first and fourth rows of (8) to become linearly dependent,

$$\begin{aligned} n_i c_{xi} + n_{ii} c_{xii} + n_{iii} c_{xiii} + n_{iv} c_{xiv} &= \bar{F}_1, \\ z(n_i c_{xi} + n_{ii} c_{xii} + n_{iii} c_{xiii} + n_{iv} c_{xiv}) &= \bar{F}_4, \end{aligned} \tag{12}$$

as well as the second and third rows of (8),

$$\begin{aligned} n_i c_{yi} + n_{ii} c_{yii} + n_{iii} c_{yiii} + n_{iv} c_{yiv} &= \bar{F}_2, \\ -z(n_i c_{yi} + n_{ii} c_{yii} + n_{iii} c_{yiii} + n_{iv} c_{yiv}) &= \bar{F}_3. \end{aligned} \tag{13}$$

Note that such a common kinematic configuration (standing straight and level on flat ground) causes a singularity in attempts to solve the force distribution problem using arbitrary additional force constraints. This singularity would require that

$$z\bar{F}_1 = \bar{F}_4, \quad -z\bar{F}_2 = \bar{F}_3. \tag{14}$$

Although this may seem to be a special case, it lends insight into an underlying model for the stance mechanics. We can express the location of a center of pressure (abbreviated COP, sometimes called the Zero Moment Point or ZMP) below the robot as

$$x_{cop} = \sum_i n_i x_i, \qquad y_{cop} = \sum_i n_i y_i. \tag{15}$$

Thus, we discover that (14), when simplified, produce the following relationships:

$$x_{cop} = \frac{zF_x}{F_z} - \frac{M'_y}{F_z}, \qquad y_{cop} = \frac{zF_y}{F_z} + \frac{M'_x}{F_z}. \tag{16}$$

These correspond to a simple single leg model of the mechanics of the robot, which is shown in Fig. 3. (Note that z is typically negative.) M'_x and M'_y indicate the effect of the previous assumptions ($C_{1N} = I$ and $z_i = z$), and are addressed in the Appendix.

To solve for the force distribution, we enforce the mechanics described by this single leg model as a suitable representation of the locomotion of the robot. Once the components of the virtual forces, $\underset{\sim}{F}$ and $\underset{\sim}{M}$, are chosen, we can determine a desired COP position directly from (16). Locating the COP as such satisfies the singularity and allows us to drop the third and fourth rows of (8). This is equivalent to achieving the instantaneous, virtual presence of the single leg model shown in Fig. 3. By choosing an intuitive function to minimize,

$$E_n = \frac{1}{2}\left(\sum_i (n_i - n_i^*)^2\right), \tag{17}$$

and remembering the three constraints of (6) and (15), we can solve for the weight distribution across the robot. n_i^* represents a desired vertical load responsibility for each leg, usually set to 1/L. Once all n_i are known, the rectangular matrix and right side of (8) are known. Based upon biological observations [20], we know that cockroaches produce forces in directions related to the attitude of each leg (although this is obviously task and context dependent). Viewing the first, second, and fifth rows of (8) as constraints, we can introduce another cost function,

$$E_c = \frac{1}{2}\left(\sum_i (\Delta c_{xi}^{\ 2} + \Delta c_{yi}^{\ 2})\right), \tag{18}$$

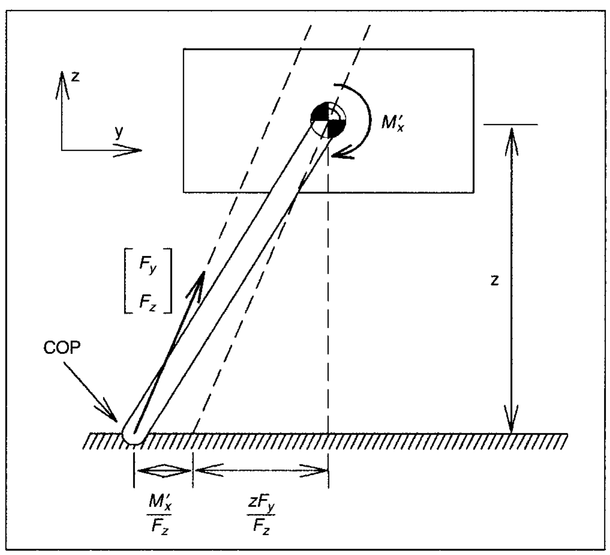

Fig. 3. Single leg model of robot mechanics.

where

$$\Delta c_{x\ell} = c_{x\ell} - c_{x\ell}^*, \quad \Delta c_{y\ell} = c_{y\ell} - c_{y\ell}^*. \tag{19}$$

Minimizing E_c will encourage each leg to push in a preferred, animal-like direction. $c_{x\ell}^*$ and $c_{y\ell}^*$ are determined by minimizing joint torques in the leg ℓ. (The form of E_c was chosen for computational efficiency. Other more isometric functions could be used.)

Results

This algorithm has been successfully implemented, and is able to control the posture of Robot III in the presence of disturbances, as well as in response to commanded body positions and orientations. Although not discussed here, the algorithm can be modified to maintain posture while legs lift and plant. In all cases, independent of the number of legs in stance, the same methods can be used.

The following two figures describe a test in which the robot was pushed while standing. These disturbances amounted to the operator standing to the right of the robot, and vigorously shoving the robot to its left with both hands [7]. In some cases the robot was shoved with a single hand in the abdomen or head areas. As a reference for the following figures, these shoves from the robot's right side caused it to sway in the lateral, or y, direction. Virtual springs, attached to the body reference frame, cause the robot to maintain a standing position.

Fig. 4: While standing, the robot was shoved repeatedly. Each arrow indicates a disturbance. The robot swayed and returned to a nominal standing position. "y pos" indicates the y, or lateral, position (see Fig. 2) of the body. "y cop" is the y location of the COP. The COP moved to counteract the disturbances. The COP was slightly negative because the robot perceived a small roll error (lean to left). Stiction in the cylinders caused the initial and final body positions to be slightly different.

Fig. 5: Corresponding to Fig. 4, this figure shows how vertical load responsibility was transferred to the left side legs as the COP moves to counteract the disturbances. "left/right n" is the ipsilateral sum of n_ℓ values.

One particularly remarkable result is given the robot's mechanical characteristics, and using this controller, the robot is able to easily lift a payload equal to its own body weight. Fig. 6 shows Robot III lifting a 30 pound payload suspended below the robot with cables. The robot is able to do "push-ups" while lifting this payload.

Another very attractive result involving this algorithm is computational simplicity. As implemented above, the largest procedural calculation is the solving of three different 3x3 systems once per cycle. This occurs once when C_{1N} is estimated and could be eliminated with a suitable attitude sensor on the body. However, no such sensor exists in the cockroach. The other two instances arise from minimizing E_c and E_n.

Conclusions

This paper presents two main contributions. The first is that the force distribution problem for a multilegged system such as Robot III has *already* embedded within it a single leg model which intuitively describes the mechanics. This model is derived mathematically, yet is intuitive and connects well with previous observations by both biologists and roboticists [21]. It is central in solving the redundancy problem and produces a computationally simple algorithm for controlling posture during locomotion. The second point is that this algorithm has been successfully implemented on a complex 24 DOF cockroach-like robot. The resulting controller is able to control all six three-dimensional DOF of the body, and should provide an excellent basis for general locomotion.

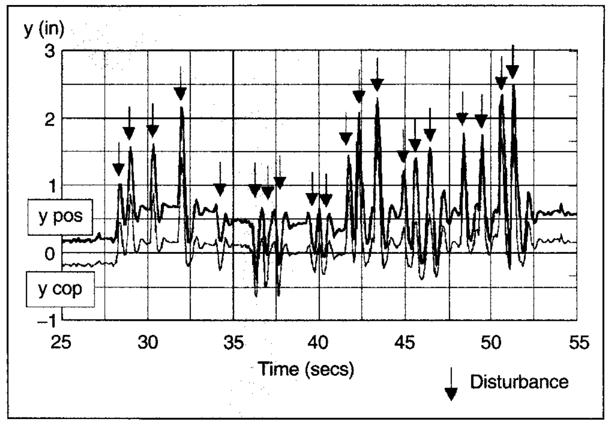

Fig. 4. Disturbance rejection while standing.

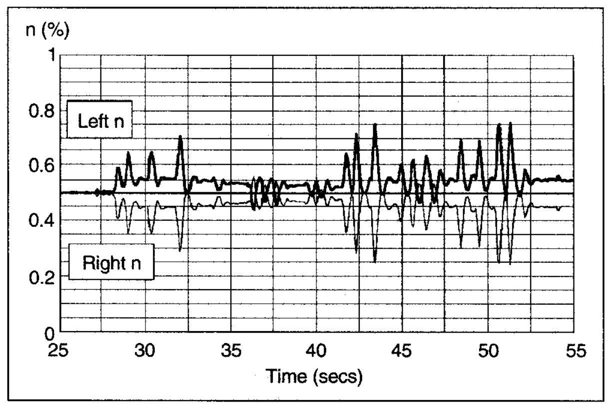

Fig. 5. Vertical load transfer to move COP.

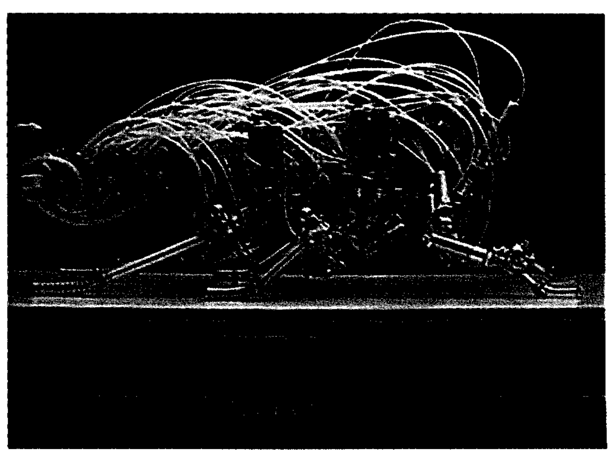

Fig. 6. Robot III lifts a 30 pound payload.

Acknowledgments

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Appendix

Here we address our previous assumptions, which means we relax the linear dependence indicated by (12) and (13). This is equivalent to determining which equations in (8) should be used as constraints in minimizing E_c. Clearly, since we locate the COP to satisfy (16), we are free to drop the third and fourth relationships when our assumptions apply. This also holds when $C_{1N} \neq I$. Premultiplying (1) by C_{N1} yields

$$\underset{\sim}{M}'_{\ell} = C_{N1} \underset{\sim}{M}_{\ell} = [C_{N1} \underset{\sim}{\tilde{W}}_{1\ell}] \underset{\sim}{F}_{\ell} = \tilde{p}_{\ell foot} \underset{\sim}{F}_{\ell}, \tag{20}$$

where

$$\underset{\sim}{M}' = C_{N1} \underset{\sim}{M} = \sum_{\ell} \underset{\sim}{M}'_{\ell} \ . \tag{21}$$

Eq. (8) can be rewritten in terms of $\underset{\sim}{M}'$, removing the explicit dependence on C_{1N} from the left side, and producing the same linear dependencies. When the feet are not at equal z_{ℓ} locations, it is necessary to include the third and fourth equations as constraints. In doing this, we replace $z \rightarrow z_{avg}$ in (16). Enforcing these final constraints may typically not be necessary. We believe that it may be possible to "dwell" around this model even on rough terrain by adjusting body orientation.

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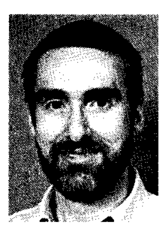

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