TerminatorBot: A Novel Robot with Dual-Use Mechanism for Locomotion and Manipulation

Richard M. Voyles, *Senior Member, IEEE* and Amy C. Larson *Member, IEEE*

***Abstract*— As part of a massively distributed heterogeneous system, *TerminatorBot*, a novel, centimeter-scale crawling robot has been developed to address applications in surveillance, search-and-rescue, and planetary exploration. Its two 3 degree-of-freedom arms, which stow inside the cylindrical body for ballistic deployment and protected transport, comprise a dual-use mechanism for manipulation and locomotion. The intended applications require a small, rugged, and lightweight robot, hence the desire for dual-use. TerminatorBot's unique mechanism provides mobility and fine manipulation on a scale currently unavailable. To facilitate manipulation, we have also developed a specialized force/torque sensor. This new sensor design has a biased distribution of flexures, which equalizes force and torque sensitivities at the operational point. This paper describes the mechanism and design of TerminatorBot, the specialized force/torque sensor, and the mechanism-specific gaits.**

***Index Terms*— robotics, mobile manipulation, force sensor, TerminatorBot**

Fig. 1. *TerminatorBot climbing through a cinderblock on a mock search and rescue mission. Using the narrow-passage gait, TerminatorBot can crawl through spaces that are equal to the width of its body.*

I. Introduction

Mobile robots are moving out of the lab and into the real world. To meet the resulting challenges, robots (or systems of robots) must be rugged, robust, functionally versatile, and not too expensive. A massively distributed heterogeneous system provides versatility and robustness, and if the majority of the mass is achieved with small-scale robots (on the order of centimeters), the cost is manageable provided that commercial off-the-shelf components can be used. Also, small-scale robots can expand system functionality otherwise unachievable. As part of a heterogeneous system for applications such as search-and-rescue and planetary exploration, we present the novel *TerminatorBot*, also known as the CRAWLER Scout (for Cylindrical Robot for Autonomous Walking and Lifting during Emergency Response - *see* Figure 1). This small-scale robot is lightweight and versatile due to its dual-use mechanism for manipulation and locomotion. While not yet fully hardened, it is intended for ballistic deployment, like other members of the Scout team [1]. This addresses the problem of gross locomotion for small-scale robots with limited power.

TerminatorBot (named after the *Terminator* from the movie of the same name) is a two-limbed, crawling robot whose body is supported by the environment during locomotion, similar to most cold-blooded animals. Limbs provide a significant advantage over wheels in uneven terrain, and TerminatorBot's limbs can also be used to manipulate objects. This dual-use design is key to keeping the robot both lightweight and small. Small robots make possible covert surveillance and provide accessibility to spaces otherwise unreachable by humans, canines, or the currently available commercial robots. This has obvious implications in buildings felled by war or earthquake. And, as stated above, small-scale reduces manufacturing costs, which consequently makes feasible a massively distributed, thus redundant, system. An army of robots may be sent out into dangerous, unpredictable environments with an increased chance of system success, despite a high attrition rate.

TerminatorBot was developed as part of a massively distributed heterogeneous system, as described in Section II, but for this paper, we focus on the capabilities of the TerminatorBot, individually. The description of the distributed system as a whole is beyond the scope of this paper. In Section II, to demonstrate the uniqueness of TerminatorBot, we review both the long history of crawling/walking robots and the less-explored area of mobile manipulation. Section III details the mechanism and design of TerminatorBot, highlighting the features that we think make it well suited to the proposed applications. In Section V, we describe the locomotion of TerminatorBot. Section IV reviews a specialized force/torque sensor designed for the dual-use mechanism. Finally, we summarize this work and discuss our future research goals, including potential configurations of TerminatorBot at the system and individual levels.

Manuscript received February 4, 2003; revised June 11, 2003. This work was supported in part by the DARPA Distributed Robotics program under contract MDA972-98-C-0008. Graduate fellowship support was also provided by the Louise T. Dosdall Fellowship from the University of Minnesota.

R.M. Voyles and A.C. Larson are with the Department of Computer Science and Engineering, University of Minnesota, 200 Union Street SE, 4-192 EE/CS Bldg, Minneapolis MN 55405 (voyles@ and larson@cs.umn.edu).

II. RELATED WORK

TerminatorBot was originally developed to complement the functionality of the Scout [1], which is a small-scale rolling robot with limited hopping capability. Developed at the Center for Distributed Robotics at the University of Minnesota, the Scout is a test bed platform for research on embodied, heterogeneous, massively distributed systems with real-world application. Its form-factor satisfies cost, deployment, and stealth requirements. One of the primary applications is covert surveillance inside man-made structures. Wheels are ideal for this environment, but mobility becomes a problem in natural and rubbled settings. Obviously, crawling robots have a significant advantage in very uneven terrain because locomotion is not dependent on a continuous clear path as it is for wheels. Instead, walking robots only require clear footfalls. TerminatorBot falls between the two as it only requires clear footfalls to get traction, but a continuous path must be clear enough for sled-like dragging of the body by the limbs.

The first of the modern era multi-legged robots was a teleoperated quadruped developed by Liston and Mosher at General Electric [2]. McGhee [3], Gurfinkel et al., [4] and Hirose [5] developed the first autonomous multi-legged walkers based on static control in the early 1980's. Soon after, Kato et al. [6], and Miura and Shimoyama [7] developed the first of the autonomous bipedal robots. Since then, a plethora of walking machines have been developed ranging from 8-legged to 1-legged (e.g. AIBO [8], Monopod [10], RHex [11], P2 [12], Tekken [13], etc.) Some of these have been statically balanced, some dynamically balanced, but all of them are true walkers in the sense that the full body weight is supported by the limbs.

Biological evolution, on the other hand, has developed a large class of mechanisms that don't fully support their own weight. Most walking creatures are warm-blooded, but their cold-blooded counterparts – snakes, turtles, crocodiles, fish, etc. – tend to rely on their environments to support their weight. These efficient, but usually slow, forms of locomotion help the ectotherms (cold-blooded animals) keep their total energy consumption 10 to 50 times less than comparable endotherms (warm-blooded animals). Likewise, a number of reptile-like robotic mechanisms have evolved, such as PolyBot [31], snakes [16], [17], and the Golem project [18]. Although there are several multi-limbed robots, to our knowledge there are only a few that achieve locomotion by dragging their bodies [19]–[22] with limbs. Of these, only TerminatorBot drags itself without passive or active wheels. Although body drag loses energy to friction, it conserves a great deal during lift and reduces complexity in maintaining balance. Thus, the payoff is in a lighter, smaller mechanism. Additionally, due to TerminatorBot's design for ballistic deployment, gross locomotion is of less concern because ballistic locomotion is entirely powered externally.

Research into mobile manipulation is more recent and less extensive. Probably the most explored topic is cooperative manipulation for the transport of objects, such as [23], [24]. The most common form of a single robot performing mobile manipulation is a mobile base with a mounted arm [26], [27], of which a commercially available example had been available from Nomadic Technologies. Typically, the base and arm are treated disjointly. To our knowledge, there are few robots whose mechanism could be used for both locomotion and manipulation, but among them are SM^2, PolyBot, Mobipulator, SMC Rover, ASTERISK, and MELMANTIS.

SM^2 [29] is an inchworm-like robot with grippers at each end. It is on a larger scale than TerminatorBot and the locomotion capabilities are specialized for repair and inspection of the space station. Like TerminatorBot, limbs can be used for both locomotion and manipulation but not simultaneously. PolyBot [31], the Mobipulator [32], and some snake robots have the ability to transport objects using whole body manipulation, but do not have fine manipulation control. There have been several studies of brachiating robots (e.g. [33], [35], but these limbs were solely for locomotion, not manipulation.

The SMC Rover [36] is a small-scale robot with a dual-use mechanism for locomotion and manipulation. This mechanism consists of the main rover, which is transported by its child rovers. Each child rover consists of a manipulator arm that is attached to a body/wheel and has a gripper/castor-wheel as an end-effector. The gripper is a clamping device that can hold tools (or the main rover body), but cannot perform fine manipulation. ASTERISK [37] and MELMANTIS [38] are similar to TerminatorBot in their dual-use mechanism of limbs. These robots each have six limbs positioned equidistance around a circular body. Manipulation results from coordination of multiple limbs (as opposed to an end-effector). Both are about 4 times the size of TerminatorBot and require control and coordination of more than 20 motors each.

Insects often serve as inspiration for robot design, such as those above, as well as [40], [41] (cockroach-inspired) and [42] (cricket-inspired), to name a few. Gait design for these robots can be very complex. There is a growing body of research dedicated to the development and refinement of gaits for efficient, effective motion (some examples are [43], [46]). Currently, TerminatorBot gaits are biologically-inspired, but user-evolved. We can borrow from this area of insect robotics and gait generation for future automatic gait design.

III. MECHANISM AND DESIGN

As stated above, TerminatorBot's unique mechanism design was developed to meet size and deployment constraints. The Scout application domain ([1]) demands the form factor of a 40mm diameter cylinder capable of high-g ballistic deployment. The Scout robots, with their polycarbonate shells, meet the 40 mm form factor constraint and a medium-g ballistic test. The current TerminatorBot prototype is two-times oversize with a sled-like acrylic cylindrical shell with a diameter of 75 mm and a length of 205 mm. The brittle acrylic shell and greater mass make medium-g deployment unrealizable, but the structure has been designed with attention to distributing energy and a polyvinyl chloride shell is in development to permit low-g ballistic deployment.

The robot has only two arms, keeping it small and lightweight, yet each has 3 degrees-of-freedom (DoF) for greater articulation. The arms can fully stow inside its body, which makes ballistic deployment possible and increases the strength of the structure. The cylindrical shape is solely to allow barrel-launched deployment, but a rectangular body is also being fabricated to provide better orientation stability.

The standard tips of the arms are hemispherical shells providing the robot with both locomotive and manipulative capabilities. The claw-like concave side is useful for traction during locomotion and for digging in light soils. The arms flip 180 degrees, exposing the convex sides for manipulation. These surfaces are like fingertips and provide a fixed center of rotation for objects moving across the spherical surface. Coupled with force/torque sensors, this can be modeled as a passive, but sensable, fourth joint during manipulation.

Each of the 3-DoF arms has 2 links that extend to 170 mm. The first link (i.e. shoulder to elbow) can move 190 degrees within the plane parallel to the ground. It also has 360 degrees of free rotation about the principal axis (roll). The second link (i.e. elbow to fingertip) can fold into the first link and can rotate 315 degrees from that folded position.

Two gearmotors housed within the body drive the 2-DoF shoulder joint of the first link through a differential. This arrangement couples the torque of both motors through the same axis of rotation for pure motions around the principal axes. The gearmotors have a ratio of 275:1 and an additional reduction stage in the form of a 15:1 worm gear, for a total gear ratio of 4125:1. The worm gear prevents back-driving the motors. Encoders on each motor provide position feedback. A right-angle gear arrangement transfers torque to the 1-DoF elbow joint that drives the 70 mm second link. The first link, which is 100 mm in length and 23 mm in width, houses the elbow joint's gearmotor and encoder. Torque sensors are incorporated directly into the elbow joint for precision manipulation and servoed back-drivability of the gear train. The Denavit-Hartenburg parameters and the tool transform that describes the final link with the hemispherical tip attached are:

L	a	α	d
1	19.7	0	0
2	0	$\pi/2$	100
3	0	$-\pi/2$	0

$$, \quad {}^{3}_{T}A = \begin{bmatrix} 1 & 0 & 0 & -10 \\ 0 & 0 & 1 & 84 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

The current design is fabricated almost entirely out of metal and weighs in at 650 grams in tethered configuration (without batteries). For tetherless operation under local control of the on-board microcontrollers, two 28-gram lithium-ion batteries are added with sufficient capacity for about 30 minutes of continuous locomotion on a level, rocky surface. Injection-molded plastic components can reduce the weight significantly as the motors contribute only about 230 grams.

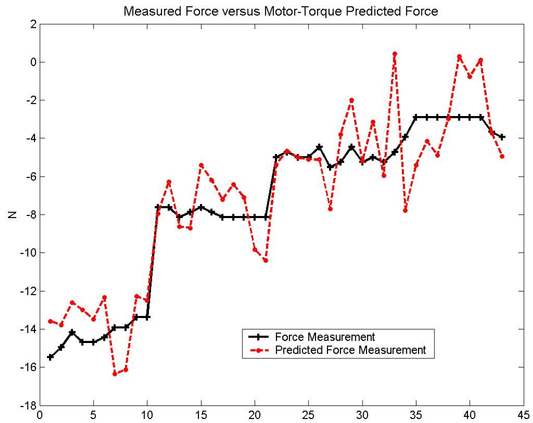
To determine motor and gearbox size, we used SimMechanics to create an idealized, dynamic model to estimate peak torque at each joint and to estimate power consumption for various proposed gaits. After construction, we compared model estimates to measured total current for the bumpy wheel and swimming gaits (described in Section V). Estimates were determined from the model by translating estimated torques to currents using motor specifications. Because we only modeled a few sources of coulomb and viscous friction (and crudely at that), we subtracted out a baseline profile of current measurements with the robot off the ground (which we surmise was friction dominated). The idealized predicted currents underestimated measured current by 74% for the bumpy wheel gait and 50% for the swimming gait. To test our assumption that the baseline measurements (and the bulk of the error) were friction dominated, we added a 1 kg mass (which is 2.5 times the body weight, not including arms) to TerminatorBot and the model. The new predictions underestimated measured current by 36% for bumpy wheel and 18% for swimming – a significant improvement over the unweighted estimates and a confirmation of our assumption of friction dominance.

The TerminatorBot prototypes are tethered for remote-brained control, but we are constructing on-board processing for complete autonomy. Currently, a custom-built microcontroller interface resides on-board for generation of pulse-width modulation (PWM) and housekeeping functions as well as limited tetherless functionality. But for convenience of code development and relatively high computational power (for forward and inverse kinematics of the limbs), we keep the robots tethered to a PC. A multi-function I/O board on the PC interfaces with the on-board electronics to write motor commands and read encoder angles. A compact, object-based real-time scheduler was developed, based on the Chimera real-time operating system [48]. The scheduler is not fully object-oriented (inheritance and dynamic memory allocation are not amenable to real-time control), but provides an interface with a variety of methods for real-time control that simplify programming. These methods are based on prior work in port-based objects [48]. Trajectory generation, node control, and low-level PD control are all embedded into port-based objects for the scheduler to dispatch on the PC. Non-preemptive multi-tasking can be used to implement the scheduler on all but the smallest of microcontrollers. To guarantee tasks meet their deadlines in the non-preemptive case, the use of real-time coroutines [49] is required.

Dynamic, interactive control is achieved with a menu-based user-interface on the PC and with a multi-modal graphic interface on the pocketPC running WindowsCE. This PDA-based interactive control of TerminatorBot is a powerful tool for experimentation, program development, and in-field operation. The PDA user-interface includes a 3D wireframe simulation of TerminatorBot for intuitive shared control. The PC currently acts as a communications hub for PocketPC's linked by serial ports. Command fusion between autonomous software agents and human directives is achieved by a weighted sum of user inputs from the PDA and autonomous commands from on-board modules, such as visual servoing. As we progress to an untethered, portable TerminatorBot, the PDA communication will migrate to IEEE 802.11b wireless.

IV. Specialized Force/Torque Sensor

For precise control of grasping and for autonomous gait adaptation, the TerminatorBot needs to sense forces at the point of contact. It is possible to estimate tip contact forces from motor torques and the inverse of the Jacobian, but this method proves to be too noisy for autonomous, precise



..

Fig. 2. *A plot of actual versus predicted force measurements using motor encoders. Predictions were based on motor torque values generated in closed-loop control. Actual measurements were taken from a Lord force/torque sensor.*

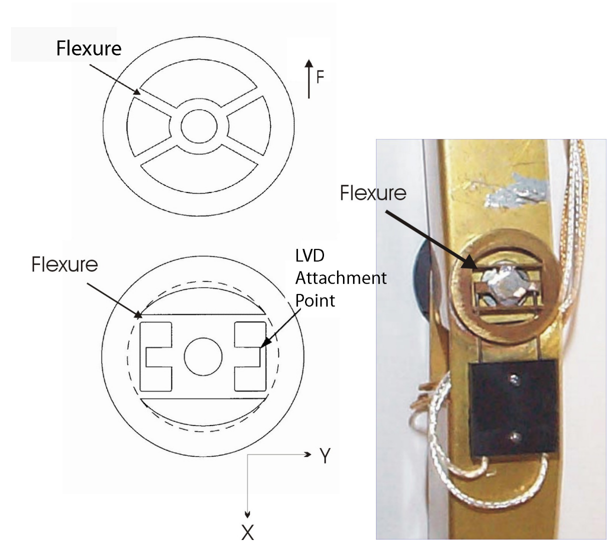


Fig. 3. *(top left) A traditional torque sensor, which has a tendency for torques to saturate the sensor more easily than forces. (bottom left) A torque sensor with biased flexures, for equalizing force and torque sensitivities. (right) The specialized sensor attached to the elbow of TerminatorBot.*

closed-loop manipulation. We examined the repeatability of force estimates based on motor torques over multiple trials for a fixed configuration of our limb. Figure 2 shows the results of our analysis. We recorded force measurements from TerminatorBot pushing down on a Lord force/torque sensor. Predicted measurements were based on motor torque values, which are generated during closed-loop control of the motors. On average, the predicted measurements were off by 200 gf (approximately 2N). This is tolerable when applying large forces or when only relative changes are important, such as for self-adaptation during locomotion. But during manipulation, TerminatorBot will typically be applying forces within this range of the error or only small multiples beyond. Therefore, to facilitate fine manipulation, the TerminatorBot has force/torque sensors embedded within the structure of the elbow joints between the driven shaft and the link structure for accurate sensing of contact forces at the tip.

A common problem with multi-axis force sensors is the tendency for torques to saturate the sensor more easily than forces, due to unknown and often variable moment arms. The impact of this is that a stiffer sensor (lower in resolution) must be chosen in order to accommodate the wider range of torque values. Force resolution then suffers, which is often of more interest than the torques.

A torque sensor can be embedded (and co-located) within a joint by placing radial flexures between the drive axle and link structure (as in Figure 3). The outer rim is rigidly attached to the link while the inner hub is rigidly attached to the axle. Applying a torque to the drive axle will cause the flexures to bend slightly, in proportion to torque. This bending can be sensed to provide an accurate torque measurement that is uncorrupted by friction or other nonlinearities of the gear train. The two pairs of opposing flexures are not perpendicular. Instead, they are biased to be sensitive to forces in the indicated direction, as well as to torques around the hub. This increases the sensitivity to forces, but, alone, cannot equalize the sensitivity of forces and torques.

The TerminatorBot force/torque sensor (Figure 3) has a unique design aimed at equalizing the forces and torques. By rotating the flexures so they are closer to perpendicular to the primary force of interest, instead of radially as in the traditional sensor, the ratio of force and torque sensitivities can be adjusted. We chose to make the flexures exactly perpendicular to the X axis because Y forces manifest themselves as the torque. This makes each sensor wheel essentially insensitive to forces in the Y-direction through the elbow. A force through the elbow in the Y-direction will result in compression and tension of the beams, which have minimal effect on the strain gages in comparison to bending modes. Sensitivity to forces in the Z-direction is achieved by differencing sensor wheels placed on opposite sides of the elbow. This results in sensitivity to three axes at the tip of the forearm (X, Y, and Z). The tip of the forearm is in the +X-direction.

To choose sensor dimensions, we approximated a solution by noting that forces at the tip parallel to the forearm (X-direction) cause the sensor to deflect like two pure fixed beams, producing a strain in the flexures:

$$\varepsilon_x = \frac{12 l F_x}{32 E a^2 b} \tag{1}$$

where l is the length of a flexure in Figure 3, F_x is the Force in x, a and b are the dimensions of the flexure cross section, and E is the Young's modulus of the material.

What is less obvious is that forces perpendicular to the forearm (in the Y-direction, creating large torques about the elbow) also cause the sensor to deflect like two fixed beams. The difference is half of the fixed beam appears to be inverted, but the fixed beams do not experience a pure perpendicular load. (This would be the conventional, radial design.) Instead the beams can be decomposed into two fixed beams coupled with four beams in compression/tension. The stiffness of these coupled beams sum, therefore the stiffness of the beams in compression/tension dominate. As a result, the strain resulting from forces acting in the Y-direction is

$$\varepsilon_y = \frac{6ldF_y cos(\phi)}{EbR(l^2 + 2a^2)} \quad (2)$$

where ϕ is the angle the flexure makes with respect to the radius, R is the radius of the rim of the sensor wheel, and d is the length of the link. In fact, this formulation ignores a small moment that results because the flexures are not infinitely stiff. We can also neglect the a^2 term in the denominator because l^2 dominates. From these two formulas we can attempt to equalize the sensitivity to forces in the two directions.

The radius of the sensor wheel is fixed by the size of the limb and the minimum thickness of the beams, a is limited by fabrication constraints. The length is as long as possible, within the limits of the radius. The free variables that are left are the depth of the sensor, b, and the angle of the beams with respect to the radius, ϕ. We aimed for a 2:1 ratio of torque to force sensitivity and then rounded the results to one decimal place to reduce the chance of errors at the machine shop. The estimated ratio of sensitivities was 1.72.

With this design, compressive stress can create a problem in cross-coupling. Vischer and Khatib [50] determined unbalanced longitudinally-induced stresses on the beams of a strain gage sensor can lead to significant corruption of the signal. To counteract that possibility, decoupled sensing elements are suggested that are insensitive to longitudinal stress.

Vischer and Khatib determined the strain, ε_s, resulting from torque, T_s, on a torque sensor such as that in Figure 3 is:

$$\varepsilon_s = \frac{3(R-r)(5R+r)T_s}{16Ea^2b(R^2+Rr+r^2)} \quad (3)$$

where R and r are the outer (rim) and inner (hub) radii of the flexures in Figure 3, E is the Young's modulus of the material, and a and b are the dimensions of the cross section of the flexures. They formulated the cross-coupling problem as a signal-to-noise problem, noting that a radial force, F_r, would produce a "noise" strain, ε_n, such that:

$$\frac{\varepsilon_s}{\varepsilon_n} = \gamma \frac{T_s}{F_r} \quad (4)$$

where

$$\gamma = \frac{3(5R+r)((R-r)^2+a^2)}{8a(R-r)(R^2+Rr+r^2)} \quad (5)$$

In [50], F_r was an independent variable that resulted from radial forces applied to the sensing wheel by the mechanism. In our case, the radial forces result from compression of the flexures and are dependent on the applied torque:

$$F_r = \frac{T_s}{R} sin(\phi). \quad (6)$$

Following that line of reasoning, and calculating that the compressive stresses along the axis of the flexures could comprise a significant variation due to uncertainty in machining of the beam thickness, we designed the TerminatorBot force/torque sensor to accommodate differential variable-reluctance transformers (DVRT) instead of strain gages. (DVRTs are similar to linear variable differential transformers - LVDTs.) The DVRTs are insensitive to the longitudinal stresses imposed by the non-radial arrangement of flexures (F_r). Since strain gages are considerably less expensive than DVRTs, we also installed strain gages on the flexures to compare the performance of the two methods of transduction.

Much to our surprise, the strain gages exhibited superior performance in comparison to the DVRTs. The plot of measured force versus applied force for both the strain gages and the DVRTs is shown in Figure 4. We focused our tests on forces below 200 gf – the region in which motor current measurements are unreliable. As the figure indicates, the strain gages are quite linear with low error and no measurable hysteresis. The goodness of fit is 0.99 for forces along the elbow and 0.98 for torques about the elbow (with 1.0 being a perfect linear relationship). The DVRTs, on the other hand, score a 0.71 and 0.96, respectively. The plot of error versus measured force for the strain gages (Figure 4) show an error (including drift, noise, and hysteresis) of about 15 grams, maximum. The DVRTs reveal an error of about 100 grams (Figure 4). The actual ratio of sensitivities of the strain gages (which is highly dependent on strain gage placement) was 2.05 as compared to our design target of 1.72.

Curiously, the torque response of the DVRT appears similar to the strain gages. We remounted the transducers and repeated experiments to ensure that a faulty DVRT or attachment was not to blame, but the results repeated. Rather, we believe the differences in mechanical sensitivity of the transducers was the cause, as the signal-to-noise ratio after amplification of the DVRTs was poor. (We were able to achieve much larger signals from the strain gages, which improved the signal-to-noise of our PC-based data acquisition system.)

Clearly, the strain gages are superior and, with a noise floor of about 15 grams, are well within our needs. This is beneficial in a number of ways. First and foremost, strain gages cost tens of dollars whereas DVRTs cost thousands of dollars. Secondly, custom strain gage electronics are simpler than DVRT, so we have incorporated the electronics directly into the forearm, reducing the wire count running back to the body.

The force/torque measurements have yet to be incorporated into the software controller, but we have begun our investigation into the manipulation capabilities of TerminatorBot. Using teleoperation and a body-mounted camera, we have successfully turned knobs and lifted objects. (For a description of our miniature pop-up pan/tilt unit, see [51].) Figure 5 shows TerminatorBot lifting a Scout into an inconspicuous surveillance niche. (The Scout is incapable of either rolling or hopping into that position.) The Scout robot rolls up to the surveillance niche, but repeatedly fails to insert itself into the niche. The TerminatorBot then crawls up from behind the Scout, lifts it into position, and then frees the Scout's tail which reliably gets stuck on the lip of the niche. This assistance cannot be provided by pushing alone.

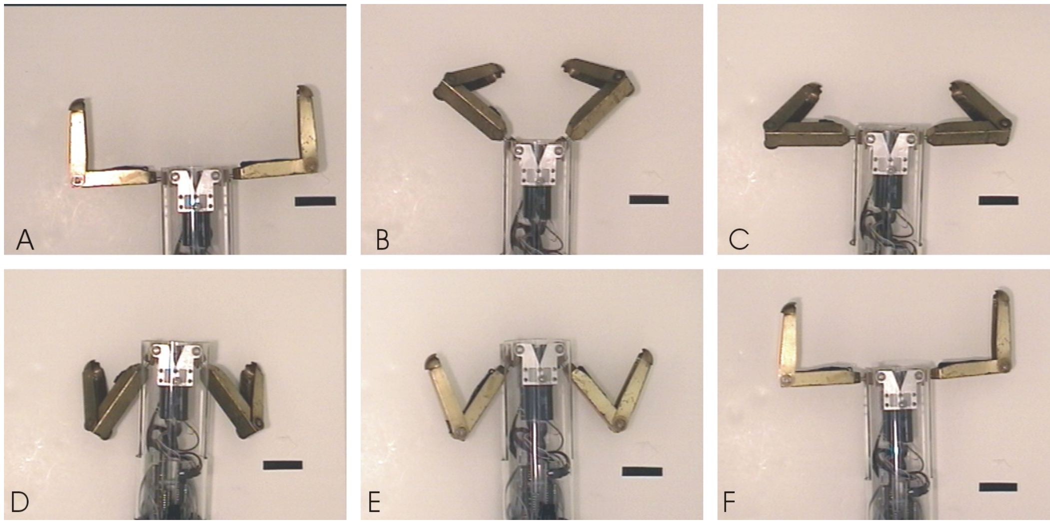


Fig. 6. *TerminatorBot locomoting using a swimming gait. A and F show a starting point to reference forward motion using the black line. In B, the arms are positioned forward of the body and rotated down to lift off the ground. The arms are rotated back while on the ground, driving the body forward as shown in B-D. The arms are lifted off the ground (E) for repositioning to start the next gait cycle.*

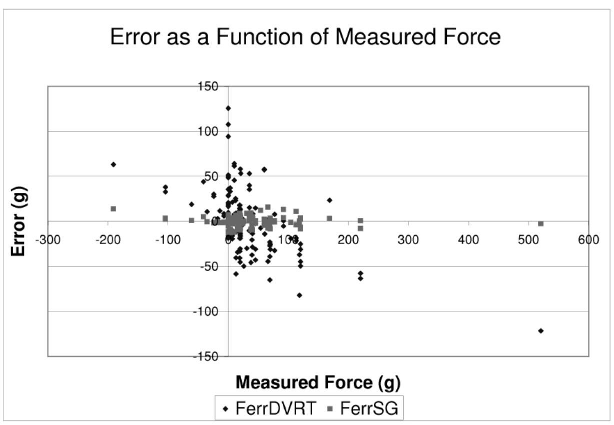


Fig. 4. *A plot of calibrations for our force/torque sensor using strain gages and DVRTs. Strain gages outperformed DVRTs. Its error in measurement is on the scale of 20 grams, versus 100 grams for the DVRTs. Strain gages also show a trend of decreased error as applied force increases.*

Fig. 5. *TerminatorBot placing a Scout onto a platform for surveillance. The Scout is incapable of rolling or hopping onto the platform but can roll itself to the platform. The TerminatorBot cannot carry things while locomoting but can crawl up behind them for assistance. This demonstrates how TerminatorBot and Scout can cooperate as part of a heterogeneous system.*

V. Locomotion

The novel mechanism of TerminatorBot suggests novel and mechanism-specific gaits. There are three forward driving gait classes: swimming, narrow-passage, and bumpy-wheel; and two turning gait classes: body-shift and differential. All gaits are a series of cycles, whose exact trajectory is determined by gait-specific parameters. This is analogous to human walking, which is a repetitive series of moves, whereby the trajectory of the leg is adjusted to accommodate different terrains and speed of movement.

Swimming gaits are characterized by stances with the arms splayed out to the sides and a full stride though much of the range of motion of the shoulder joints (Figure 6). This movement is similar to the breaststroke in swimming but is used on dry land only. These gaits are parameterized with *splay*, *lift*, *range*, *arm height*, and *speed* to adapt to terrain conditions, task demands, and power consumption. (The details of gait parameterization are to be described in a future paper on gait adaptation.)

Narrow passage gaits permit movement through enclosed spaces that are only as wide as the body (provided navigational capability is sufficiently precise). These gaits are possible due to the differential shoulder joint and unique ability of the first link to rotate around its principal axis. Motion is effected entirely forward of the robot's body as it pulls itself along.

The bumpy wheel gait is the most powerful because all four shoulder motors are coupled to drive the body forward and because forces on the elbow joint are absorbed by the structure. These gaits also make use of the ability of the differential shoulder to rotate 360 degrees. The elbows are fixed at 90 degrees and the arms "roll" like broken wheels. The current prototype does not have slip-ring electrical contacts, so continuous rolling of joint two is not permitted. Still, bumpy wheel gaits can be implemented by rolling 180 degrees, then repositioning the arms for the next cycle.

Differential turning is a modification of the swimming gait, whereby the arms are placed at different angles forward of the body. The arms move at differential speeds to reach an identical angle back of the body. This causes a reorientation during forward movement, analogous to turning of a wheeled vehicle by varying wheel speeds. The turning angle is a function of the angle difference of the arms, but this function varies according to the terrain.

Less controllable but more powerful, body shift gaits are similar to differential turning, but the body reorients without forward movement. It is achieved by placing the arms at differential angles forward of the body, effectively placing the body off-center between the two arms. Turning is achieved by rotating the shoulder joints to center the body. The turning angle is a direct translation of the angle difference.

It is not sufficient for TerminatorBot to be able to move, it must be able to move purposefully. Therefore, we implemented visual servoing using sum of squared differences (SSD) template matching [52] to track a target. SSD is an optimization algorithm that minimizes the error of pixel intensity difference between the target and its new location. The visual system tracks a specified target and calculates the positional error relative to the center of the visual field. The control system translates this real-valued error to a homing angle which it uses to select which open-loop gait type (feedforward gait pattern) to use during the next gait cycle. If the error exceeds a threshold, the control system switches to a turning gait and uses the homing angle as an input parameter (as described above), allowing the robot to home in on visual targets. As part of this work on visual servoing, we have been developing the visual measurement of gait bounce to classify the terrain immediately under the robot in order to dynamically adapt the gait parameters [53]. This work is ongoing and will be the subject of an upcoming paper.

Currently, we do not plan our footfalls using sensor information, either visual or force. Instead, we execute open-loop, cyclic gait patterns similar to RHex [11], which is loosely modeled after cockroach "scrambling" locomotion. We plan to use the force sensors in a reactive, probing mode, similar to the work of [42] in duplicating the probing reactions of a cockroach leg in crawling across a slatted surface.

VI. Conclusions and Future Work

We have described the development of TerminatorBot, a new robot design with dual-use mechanism for locomotion and manipulation. We have successfully implemented a variety of parametrizable, open-loop gaits, some of which coevolved with the design of the mechanism itself. In its current tethered configuration, the TerminatorBot is quite agile, for a robot of its size, on piles of rocks, bricks and other uneven terrain. Through teleoperation, we have also demonstrated its usefulness as a manipulator in a heterogeneous team of robots.

To enable semi-autonomous manipulation and reactive locomotion, we developed an integral 3-axis force/torque sensor with roughly isotropic sensitivity. This sensor, embedded in the structure of the elbow, shows more than adequate sensitivity with the use of strain gages, despite significant compressive loads that result by design. The sensor achieves a 2.05:1 ratio in sensitivity to forces at the tip which is very close to the linearized design target of 1.72:1. We have yet to incorporate the sensor data into the control loops for either manipulation or locomotion as we are developing on-board signal conditioning to reduce the wiring complexity.

We envision TerminatorBot as a versatile robot platform, which can be reconfigured physically, and in software, to accommodate its application environment. Reconfiguration may be a small modification, such as the addition of a sensor, or may be a major restructuring. We have already reconfigured two TerminatorBot's into a 4-legged walking machine, which in preliminary testing, locomoted forward by shuffling its feet.

We are currently working on de-tethering the robot, but we also envision an active-tethered version of many nodes, called TetherNet. The work of search and rescue robots at the Ground Zero site found that tethers were necessary, but problematic. By incorporating tethers as part of the design and controlling them actively, not only can we overcome power and communication limitations, but potentially solve relative localization. Finally, we are beginning the design of a slightly larger version with better power-to-weight ratio and greater articulation to explore the difficult dynamic transitions from crawling to bipedal locomotion.

Acknowledgments

We thank Monica LaPoint for her development of the PDA interface and assistance with visual servoing, and Berk Yesin for the use of his SSD tracking code.

References

[1] D. Hougan, S. Benjaafar, J. Bonney, J. Budenske, M. Dvorak, M. Gini, H. French, D. Krantz, P. Li, F. Malver, B. Nelson, N. Papanikolopoulos, P. R. ans S.A. Stoeter, R. Voyles, and K. Yesin, "A miniature robotic system for reconnaissance and surveillance," in *Proc. of the IEEE Int'l Conference on Robotics and Automation*, 2000, pp. 501–507.

[2] R. Liston and R. Mosher, "A versatile walking truck," in *Proceedings of the Transportation Engineering Conference*, 1968.

[3] R. McGhee, *Vehicular legged locomotion*. JAI Press, 1983.

[4] V. Gurfinkel, E. Gurfinkel, A. Shneider, E. Derjanin, A. Lensky, and L. Shitllman, "Walking robot with supervisory control," in *Mechanism and Machine*, vol. 16, 1981, pp. 31–36.

[5] S. Hirose, "A study of design and control of a quadruped walking vehicle," *Int'l Journal of Robotics Research*, vol. 3, pp. 113–133, 1984.

[6] T. Kato, A. Takanishi, H. Jishikawa, and I. Kato, "The realization of the quasi-dynamic walking by the biped walking machine," in *4th Symposium on Theory and Practice of Robots and Manipulators*, 1983, pp. 341–351.

[7] H. Miura and J. Shimoyama, "Dynamic walk of a biped," *Int'l Journal of Robotics Research*, vol. 3, pp. 60–74, 1984.

[8] M. Fujita, "Digital creatures for future entertainment robotics," in *Proc. of the IEEE Int'l Conference on Robotics and Automation*, 2000, pp. 801–806.

[9] R. Brooks, "Robot that walks; emergent behaviors from a carefully evolved network," in *Proc. of the IEEE Int'l Conference on Robotics and Automation*, 1989, pp. 692–696.

[10] M. Raibert, H. Brown, Jr., M. Chepponis, J. Hodgins, J. Koechling, D. Dustman, W. K. Brennan, D. S. Barrett, C. M. Thompson, J. Hebert, W. Lee, and L. Borvansky, "Dynamically stable legged locomotion," Massachusetts Institute of Technology, Tech. Rep. 1179, September 1985–1989, AI Technical Report.

[11] R. Hendorfer, N. Moore, H. Komsuoglu, M. Buehler, H. Brown, Jr., D. McMardie, U. Saranli, R. Full, and D. Koditschek, "Rhex: a biologically inspired hexapod runner," *Autonomous Robots*, vol. 207, no. 11, 2001.

[12] K. Hirai, M. Hirose, Y. Haikawa, and T. Takenaka, "The development of honda humanoid robot," in *Proc. of the IEEE Int'l Conference on Robotics and Automation*, 1998, pp. 1321–1326.

[13] Y. Fukuoka, H. Kimura, and A. H. Cohen, “Adaptive dynamic walking of a quadruped robot on irregular terrain based on biological concepts,” *Int’l Journal of Robotics Research*, in press.

[14] M. Yim, “New locomotion gaits,” in *Proc. of the IEEE Int’l Conference on Robotics and Automation*, 1994, pp. 2508–2513.

[15] E. Paljug, T. Ohm, and S. Hayati, “The JPL serpentine robot: A 12 DOF system for inspection,” in *Proc. of the IEEE Int’l Conference on Robotics and Automation*, vol. 3, 1995, pp. 3143–3148.

[16] G. Chirikjian and J. Burdick, “A modal approach to hyper-redundant manipulator kinematics,” *IEEE Transactions on Robotics and Automation*, vol. 10, pp. 343–354, June 1994.

[17] K. Dowling, “Limbless locomotion. Learning to crawl with a snake robot,” Ph.D. dissertation, Carnegie Mellon University, 1997.

[18] H. Lipson and J. Pollack, “Automatic design and manufacture of robotic lifeforms,” *Nature*, no. 406, pp. 974–978, 2000.

[19] Y.-J. Dai, E. Nakano, T. Takahashi, and H. Ookubo, “Motion control of leg-wheel robot for an unexplored outdoor environment,” in *Proc. IEEE/RSJ Int’l Conf. on Intelligent Robots and Systems*, vol. 2, 1996.

[20] H. Adachi and N. Koyachi, “Development of a leg-wheel hybrid mobile robot and its step-passing algorithm,” in *Proc. IEEE/RSJ Int’l Conf. on Intelligent Robots and Systems*, 2001, pp. 728–733.

[21] J. Müller, M. Schneider, and M. Hiller, “Modeling, simulation, and model-based control of the walking machine ALDURO,” *IEEE/ASME Transactions on Mechatronics*, vol. 5, no. 2, pp. 142–152, 2000.

[22] G. Endo and S. Hirose, “Study on roller-walker (multi-mode steering control and self-contained locomotion),” in *Proc. of the IEEE Int’l Conference on Robotics and Automation*, vol. 3, 2000, pp. 2808–2814.

[23] B. P. Gerkey and M. J. Mataric, “Pusher-watcher: An approach to fault-tolerant tightly-coupled robot coordination,” in *Proc. of the IEEE Int’l Conference on Robotics and Automation*, 2002, pp. 464–469.

[24] C. Kube and H. Zhang, “The use of perceptual cues in multi-robot box-pushing,” in *Proc. of the IEEE Int’l Conference on Robotics and Automation*, vol. 3, 1996, pp. 2085–2090.

[25] R. Emery and T. Balch, “Behavior based control of a non-holonomic robot in pushing tasks,” in *Proc. of the IEEE Int’l Conference on Robotics and Automation*, 2001, pp. 2381–2388.

[26] W. Carriker, P. Khosla, and B. Krogh, “Path planning for mobile manipulators for multiple task execution,” *IEEE Transactions on Robotics and Automation*, vol. 7, no. 3, pp. 403–408, June 1991.

[27] O. Khatib, “Mobile manipulation: The robotic assistant,” *Robotics and Autonomous Systems*, vol. 26, no. 2–3, pp. 175–183, Feb 1999.

[28] W. Morse, D. Hayward, D. Jones, A. Sanchez, and D. Shirey, “Overview of the accident response mobile manipulation system (armms),” in *Proceedings of the ASCE Specialty Conference on Robotics for Challenging Environments*, 1994, pp. 304–310.

[29] Y. Xu, H. Brown, Jr., M. Friedman, and T. Kanade, “Control systems of self-mobile space manipulator,” *Trans. on Control Systems Technology*, vol. 3, no. 2, pp. 207–219, 1994.

[30] Y. Xu, C. Lee, and H. Brown, Jr., “A separable combination of wheeled rover and arm mechanism DM^2,” in *Proc. of the IEEE Int’l Conference on Robotics and Automation*, vol. 3, 1996, pp. 2383–2388.

[31] M. Yim, D. G. Duff, and K. D. Roufas, “PolyBot: A modular reconfigurable robot,” in *Proc. of the IEEE Int’l Conference on Robotics and Automation*, vol. 1, 2000, pp. 514–520.

[32] S. Srinivasa, C. Baker, E. Sacks, G. Reshko, M. Mason, and M. Erdmann, “Experiments with nonholonomic manipulation,” in *Proc. of the IEEE Int’l Conference on Robotics and Automation*, vol. 7, 2002, pp. 2042–2047.

[33] F. Saito, T. Fukuda, and F. Arai, “Swing and locomotion control for a two-link brachiation robot,” *IEEE Control Systems Magazine*, vol. 14, no. 1, pp. 5–1, February 1994.

[34] J. Nakanishi, T. Fukuda, and D. Kokitschek, “Brachiating robot controller,” *IEEE Transactions on Robotics and Automation*, vol. 16, no. 2, pp. 109–123, 2000.

[35] H. Nishimur and K. Funaki, “Motion control of three-link brachiation robot by using final-state control with error learning,” *IEEE/ASME Transactions on Mechatronics*, vol. 3, no. 2, pp. 120–128, 1998.

[36] A. Kawakami, A. Torii, and S. Hirose, “Design of SMC Rover: Development and basic experiments of arm equipped single wheel rover,” in *Proc. IEEE/RSJ Int’l Conf. on Intelligent Robots and Systems*, vol. 1, 2001, pp. 96–101.

[37] Y. Takahashi, T. Arai, Y. Mae, K. Inoue, and N. Koyachi, “Development of multi-limb robot with omnidirectional manipulability and mobility,” in *Proc. IEEE/RSJ Int’l Conf. on Intelligent Robots and Systems*, vol. 3, 2000, pp. 2012–2017:

[38] N. Koyachi, H. Adachi, M. Izumi, and T. Hirose, “Control of walk and manipulation by a hexapod with integrated limb mechanism: MELMANTIS-1,” in *Proc. of the IEEE Int’l Conference on Robotics and Automation*, vol. 4, 2002, pp. 3553–3558.

[39] T. Arai, N. Koyachi, H. Adachi, and K. Homma, “Integrated arm and leg mechanism and its kinematic analysis,” in *Proc. of the IEEE Int’l Conference on Robotics and Automation*, 1995, pp. 994–999.

[40] D. Kingsley, R. Quinn, and R. Ritzmann, “A cockroach inspired robot with artificial muscles,” in *Int’l Symposium on Adaptive Motion of Animals and Machines*, 2003.

[41] F. Delcomyn and M. Nelson, “Architectures for a biomimetic hexapod robot,” *Robotics and Autonomous Systems*, vol. 30, pp. 5–15, 2000.

[42] M. Birch, R. Quinn, G. Hahm, S. Phillips, B. Drennan, R. Beer, X. Yu, S. Garverick, S. Laksanacharoen, A. Pollack, and R. Ritzmann, “A miniature hybrid robot propelled by legs,” in *Proc. IEEE/RSJ Int’l Conf. on Intelligent Robots and Systems*, 2001, pp. 845–851.

[43] M. Lewis and G. Bekey, “Gait adaptation in a quadruped robot,” *Autonomous Robots*, vol. 12, pp. 301–312, 2002.

[44] F. Kirchner and D. Spenneberg, “A biomimetic approach towards autonomous real world robots,” in *Intelligent Autonomous Systems*, 2002, pp. 187–194.

[45] G. Hornby, S. Takamura, J. Yokono, O. Hanagata, T. Yamamoto, and M. Fujita, “Evolving robust gaits with AIBO,” in *Proc. of the IEEE Int’l Conference on Robotics and Automation*, 2000, pp. 3040–3045.

[46] H. Kimura, S. Akiyama, and K. Sakurama, “Realization of dynamic walking and running of the quadruped using neural oscillator,” *Autonomous Robots*, vol. 7, no. 3, pp. 247–258, 1999.

[47] D. B. Stewart, D. E. Schmitz, and P. K. Khosla, “The Chimera II real-time operating system for advanced sensor-based control applications,” in *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 22, no. 6, 1992, pp. 1282–1295.

[48] D. B. Stewart and P. K. Khosla, “The chimera methodology: Designing dynamically reconfigurable and reusable real-time software using port-based objects,” *International Journal of Software Engineering and Knowledge Engineering*, vol. 6, no. 2, pp. 249–277, June 1996.

[49] P. Laplante, *Real-Time Systems Design and Analysis*. IEEE Press, 1997.

[50] D. Vischer and O. Khatib, “Design and development of high-performance torque-controlled joints,” *IEEE Transactions on Robotics and Automation*, vol. 11, no. 4, pp. 537–544, 1995.

[51] K. Yesin, B. Nelson, N. Papanikolopoulos, R. Voyles, and D. Krantz, “Active video system for a miniature reconnaissance robot,” in *Proc. of the IEEE Int’l Conference on Robotics and Automation*, vol. 4, 2000, pp. 3920–3925.

[52] B. J. Nelson and P. K. Khosla, “Vision resolvability for visually servoed manipulation,” *Journal of Robotic Systems*, vol. 13, no. 2, pp. 75–93, February 1996.

[53] R. Voyles, A. Larson, K. Yesin, and B. Nelson, “Using orthogonal visual servoing errors for classifying terrain,” in *Proc. IEEE/RSJ Int’l Conf. on Intelligent Robots and Systems*, vol. 2, 2001, pp. 772–777.

Richard M. Voyles received a B.S.E.E. from Purdue University in 1983, an M.S. in Manufacturing Systems Engineering from the Department of Mechanical Engineering at Stanford University in 1989, and a Ph.D. in Robotics from the School of Computer Science at Carnegie Mellon University in 1997. He is currently an Assistant Professor in the Department of Computer Science and Engineering at the University of Minnesota. His current research interests are in the areas of miniature, constrained robots; mobile manipulation; multi-robot coordination; programming by human demonstration; robot-to-robot skill transfer; skill-based approaches to robot programming; and haptic sensors and actuators.

Amy C. Larson received a B.S. in Computer Science from the University of Massachusetts at Amherst in 1996 and a Ph.D. in Computer Science from the University of Minnesota in 2003. Her research interests are in the area of multi-robot cooperation, learning, and urban search-and-rescue. She is currently a lecturer in the Department of Computer Science and Engineering at the University of Minnesota.