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A MESOSCALE MECHANISM FOR ADAPTIVE MOBILE MANIPULATION

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ABSTRACT

A novel, centimeter-scale crawling robot is described. Intended for military and civilian surveillance and search-and-rescue applications, the robot must be small, rugged, and lightweight with robust, reconfigurable capabilities. As a result, a dual-use design employing two arms for both manipulation and locomotion was conceived. The robot consists of two, three-degree-of-freedom arms that can stow completely inside the 75 mm diameter cylindrical body for ballistic deployment. This paper describes the mechanism and design motivation as well as three novel locomotion gaits and a fourth conventional gait. An outline for gait adaptation is suggested for future work.

INTRODUCTION

The Center for Distributed Robotics at the University of Minnesota conducts research in a variety of areas in embodied distributed agents. Although heterogeneity is a primary theme of the center, a common trait among its robots is small size. This is driven partly by an interest in massively distributed systems, for which small size is a practical concern, and partly by the dominant sponsor, DARPA, for which small size provides stealth.

Small robots are generally resource-constrained, the most precious resource being power, which equates to operational life. But most other aspects of small robots are constrained, too: computation, sensing, manipulation, and locomotion. The reason for this is not only that these resources consume power, but that every cubic centimeter of “other resource” that is added displaces a potential cubic centimeter of power. For lithium primary cells, this amounts to about 422 milliwatt-hours per cubic centimeter.

Small robots are also limited in their locomotion capabilities due to their size. As mentioned above, power is limited, which limits range, but efficient locomotors, such as wheels, cannot surmount large obstacles (relative to their radii) and require a continuous clear path. Furthermore, speed of travel is generally proportional to size. The result is that novel locomotion modes and mechanisms are required to handle the competing demands of small robots.

The subject of this paper is the *TerminatorBot*, a mesoscale mobile manipulator that uses it arms for both manipulation and locomotion. This dual-use design approach was adopted to add manipulation capability to our previous *Scout* mobile robots [1]. These robots have hard form-factor constraints because they employ ballistic locomotion for initial gross positioning. The robots are intended to be launched or thrown to the vicinity of their targets for fast traversal with minimal onboard power consumption. After initial deployment, they must rely on onboard resources to position themselves and surmount obstacles.

The proposed benefits of adding manipulators to our robots include manipulation of payloads, manipulation of the environment for camouflage (pulling objects over itself), digging into soft earth, and limbed locomotion. Space and resource constraints prevent merely adding arms to the existing *Scout* robot, hence the new design.

This paper focuses on the design of the *TerminatorBot* mechanism and the novel (and conventional) gaits that it uses for locomotion. We will briefly outline plans for gait adaptation and transitioning to manipulation, but this research is still underway.

PRIOR WORK

Mobile manipulation is an area of research that has not been extensively addressed in the robotics community. Many have placed manipulators on mobile robots (in fact, Nomadic Technologies has a commercial offering with a PUMA 560 manipulator), but they have generally been treated disjointly. Sandia, for example, has put Schilling arms on a variety of platforms for teleoperation in hazardous environments (e.g. [2]). Carriker et al integrated the path planning of low-DoF subsystems, but motion operations and design for each were treated separately [3]. Khatib has done significant work in integrating the motion control of arms and mobile bases through the Operational Space formulation [4], but has not performed visual servoing (an important goal of the TerminatorBot) nor are the mechanisms dual-use. Brachiation robots, which use arms for locomotion by swinging like a gibbon, have also received some study (e.g. [5]), but current mechanisms are incapable of manipulation.

A few robots have been considered with dual use design. SM^2 and DM^2 at Carnegie Mellon ([6] and [7], respectively) and PolyPod/PolyBot at Stanford/Xerox ([8])

are notable examples. SM^2 and DM^2 are symmetric, biologically inspired inch-worm-like robots with grippers at each end. The robots are designed to walk around the outside of the space station to perform repair and inspection tasks. PolyPod is a modular serpentine manipulator of many similar joint modules designed with both manipulation and locomotion in mind. “Platonic Beasts” [9] were developed by Pai et al with suggestions of dual-use limbs, but they were primarily studied for their robust locomotion capabilities. Finally, Mason et al have developed the “Mobipulator” [10] for extensive study of desktop mobile manipulation, but this robot possesses only differential drive wheels and no limbs for dextrous manipulation.

TARGET APPLICATIONS

The Scout robot has reconfigurable payloads and both rolling and hopping modes of locomotion, so it is quite capable. Rolling is fairly power efficient and hopping enables it to overcome obstacles, which are common for a robot only 40 mm tall. Unfortunately, while the hopping is required for practical mobility, it is rather time and power inefficient due to the inefficiency of the winch mechanism. Navigational certainty is also very low for hopping. The distance and direction of travel is poorly known and orientation in the plane upon landing is completely random.

Its small size and stealth are useful for military and civilian uses. Equipped with a camera or microphone Scouts could be used in search-and-rescue operations following natural disasters (e.g. earthquakes) or terrorist actions (e.g. Oklahoma City bombing). There is also potential interest from civilian SWAT teams in hostage situations and police standoffs. These are natural military uses, as well, particularly in urban warfare environments that involve civilians. Surveillance robots of this size could be carried and deployed by warfighters, keeping the warfighters out of the line of fire and minimizing the risk of civilian casualties in the “heat of the moment.”

While the Scouts’ dual locomotion modes are necessary to achieve many of these missions in real environments, there are concerns they may be inadequate for particular scenarios, hence the investigation of the TerminatorBot as an alternate design. For example, mesoscale robots would be most useful in search-and-rescue operations in which the damage is too severe and constricting to send in dogs (which arguably will be superior to robots in sensing for the near future). But large amounts of rubble within extremely cramped spaces may thwart both locomotion modes of the Scouts (too much rubble to roll, too little headroom to hop - see Figure 1). A crawling robot such as TerminatorBot could fill this niche in which available headroom is, on average, just a few times the rubble size.

In surveillance tasks, it is desirable for the robot to conceal itself. The Scouts will only be able to make use of existing open spaces such as underneath furniture. A robot with manipulators could actually pull objects over itself, creating its own cover and enhancing its stealth. A miniature, telescoping pan/tilt unit has been developed to facilitate such stealthy surveillance, too [11].

Figure 1: TerminatorBot in mock search-and-rescue scenario. (Robot was joint-level teleoperated for this photo.)

The idea of many small robots amassing a useful charge from small, insignificant explosives has been suggested by researchers in a number of scenarios. The main problem with this idea is that the efficiency of explosives is highly dependent on their placement. A bunch of mobile robots with no ability to manipulate would amass a rather inefficient bomb. Just one or two robots with the ability to locomote *and* manipulate could carefully place the charges, demanding many fewer trips to achieve a given objective.

Finally, in many of these scenarios, the ability to dig or burrow in light soils is beneficial. This could provide camouflage during surveillance, additional access during search-and-rescue, and an alternate detonation means during de-mining.

MECHANISM DESIGN

The TerminatorBot’s body is cylindrical to eventually allow gun-launching from an M203 grenade launcher. Two 3-degree-of-freedom (DoF) arms can fully stow inside the body for launching (Figure 2). While the ultimate goal is to fit the 40mm diameter form factor of a launchable grenade, the current prototype is approximately two times oversize with a diameter of 75 mm and maximum reach of each arm of 170 mm.

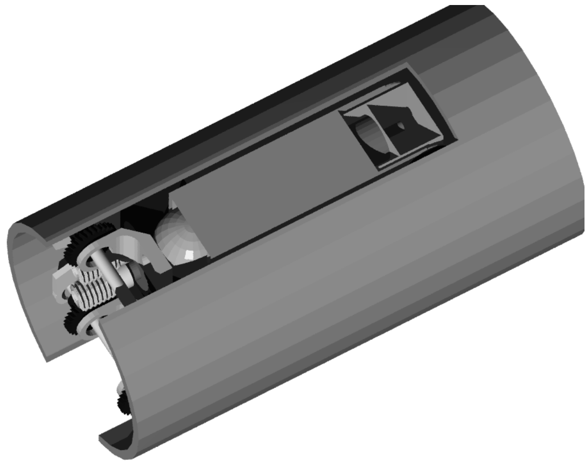

Figure 2: CAD rendering of TerminatorBot in the stowed configuration.

Two gearmotors within the body drive a 2-DoF shoulder joint through a differential. This arrangement couples the torque of both motors through the same axis of rotation for pure motions around the principal axes. Encoders on each motor provide position feedback for positioning link 1. The gearmotors have a relatively low ratio of 17:1, but an additional reduction stage in the form of a 15:1 worm gear boosts the total gear ratio to 255:1 and prevents back-driving the motors. Back-drivability, while often desirable, is bad for power conservation in this case, since the limbs have to partially support the weight of the robot in certain configurations.

The first link is 100 mm in length and 23 mm in width, allowing the inclusion of the gearmotor and encoder for the third joint within. A right-angle gear arrangement transfers torque to a traditional 1-DoF elbow joint that drives the 70mm second link. The Denavit-Hartenberg parameters are tabulated in Table 1. Below is the tool transform for locomotion (tip of claw).

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

Table 1: D-H parameters (radians and mm)

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

Incorporated into the joint are torque sensors for direct measurement of joint torque at the point of application.

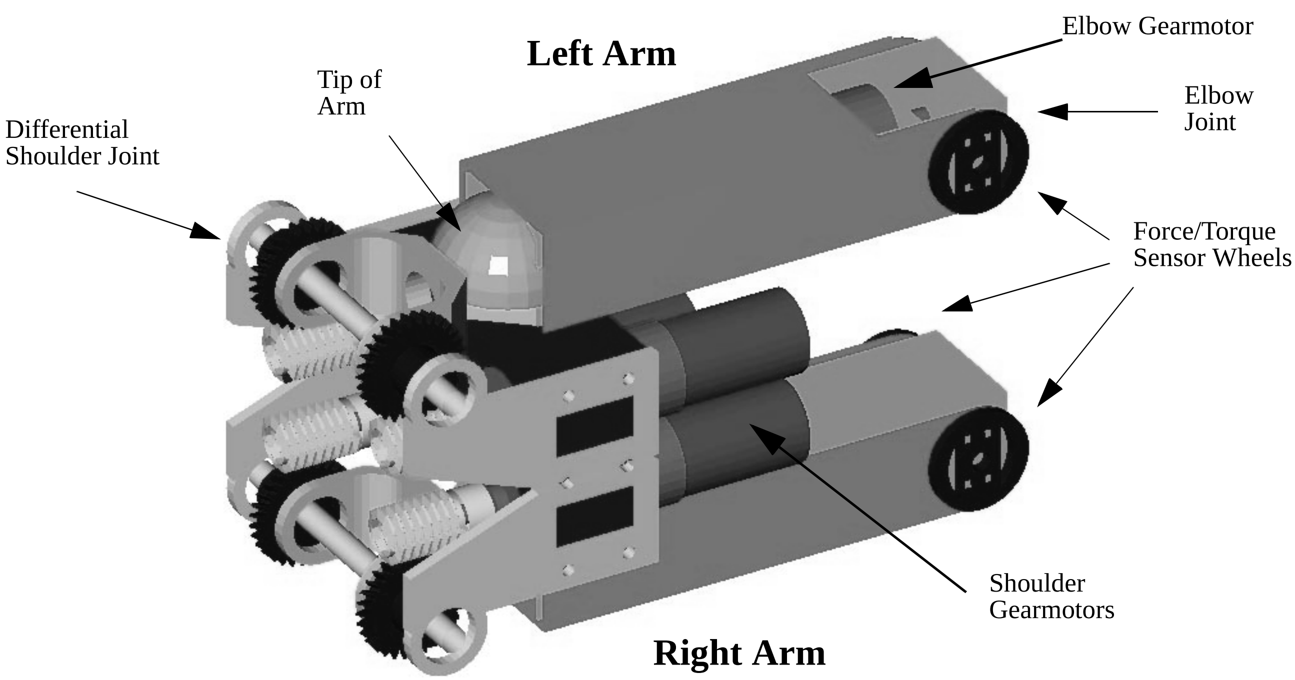

Figure 3: Internal parts of the TerminatorBot in the stowed configuration. Bearings and some other parts are not illustrated.

Force/torque sensing is incorporated for use during manipulation of objects and also to enable servoed back-drivability of the gear train when desired.

The torque sensors include a number of important design features to increase their utility. Each sensor wheel (see Figure 4) is designed to provide two axes of force/torque. A traditional torque sensor (similar to the cross-

Figure 4: 2-DoF force/torque sensor wheel for elbow joint.

section in Figure 5, but with symmetrical beams) consists of four to eight radial flexures arranged with regular spacing

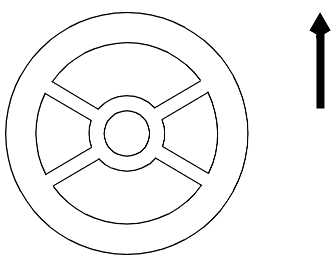

Figure 5: Cross-section of "traditional" torque sensor with radial flexures (although irregular flexure spacing is "non-traditional" - see text).

about the center point [12]. By biasing the distribution of flexures toward a single diameter, as in Figure 5, the sensor is made more sensitive to forces along **F**. As in a multi-axis

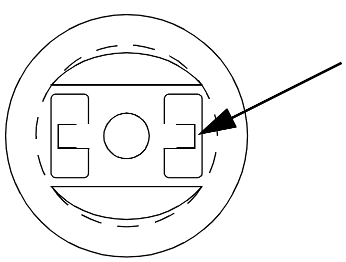

Figure 6: Cross-section of the force/torque sensor wheels used on TerminatorBot.

wrist force/torque sensor, the flexures can be used to sense multiple components. But a common problem with multi-axis sensors is maximum load capacity is dominated by torques, which multiply quickly due to the lever arm. To combat this problem, the flexures are placed off the radii and perpendicular to the force (Figure 6). For a given flexure dimension, this diminishes the torque sensitivity and increases the force sensitivity, making the response more isotropic for typical scenarios encountered in practice.

The use of strain gages on such a small device (The flexures are only 2 mm wide and 2.5 mm long) would present manufacturing problems and the compressive strains introduced by the off-radii flexures would inject noise. Instead, LVDTs (linear variable differential transformers) are mounted between the hub and the link to sense pure deflection as in [13]. LVDTs are insensitive to the noise strains experienced by the flexures and, due to their high frequency carrier wave excitation, are more immune to electrical noise produced by the motors and other sources.

Finally, two sensor wheels are employed on each joint, one on each side. This allows the measurement of a third axis of force at the manipulator tip, complementary to the other two components. This is somewhat problematic because the sensors are not collocated and it is impossible to disambiguate a force at the tip from a transverse torque. Nonetheless, the additional force axis will be valuable during manipulation as the manipulators do possess the ability to move out of plane and it is unlikely that transverse torques will come into play during manipulation of objects (which is the only time precise measurements are required).

The tips of the arms are hemispherical shells that serve a dual purpose. The concave side is claw-like and is useful for traction during locomotion and even for digging in very light soils, such as sand. When manipulating objects, the arms will flip 180 degrees, exposing the convex sides to one another. These surfaces are like fingertips and provide a fixed center of rotation for objects moving across the spherical surface. Coupled with the force/torque sensors, this can be modeled as a passive, but sensible, fourth joint on each arm during manipulation.

The assembled prototype is shown in figures 7 and 8. The arms of the prototype are 105 grams each and the body is 440 grams excluding batteries and CPU, for a total of 650 grams in mechanism alone. Currently, the prototype uses conventional PWM drivers for the six motors, but we are considering implementing a switched high current bus, similar to Pratt et al [14], to save space.

LOCOMOTION GAITS

Novel mechanisms often suggest novel and mechanism-specific gaits, as was the case with PolyPod [8] and Platonic Beasts [9]. There are four proposed classes of locomotion gaits for use on TerminatorBot: swimming gaits, narrow-passage gaits, bumpy-wheel gaits, and a dynamic rolling gait. All the gaits are used on dry land, but the "swimming gaits" are so named because of their similarity

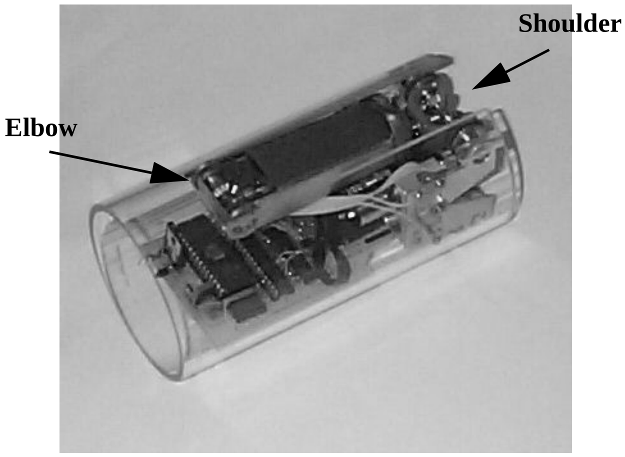

Figure 7: Assembled TerminatorBot in stowed configuration.

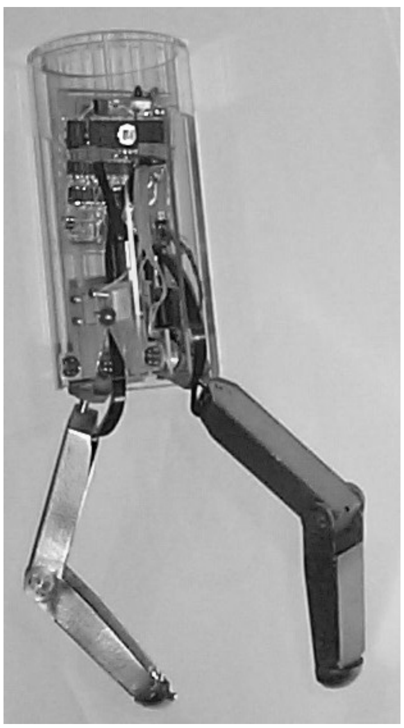

Figure 8: Assembled prototype with microcontroller for joint control in deployed configuration.

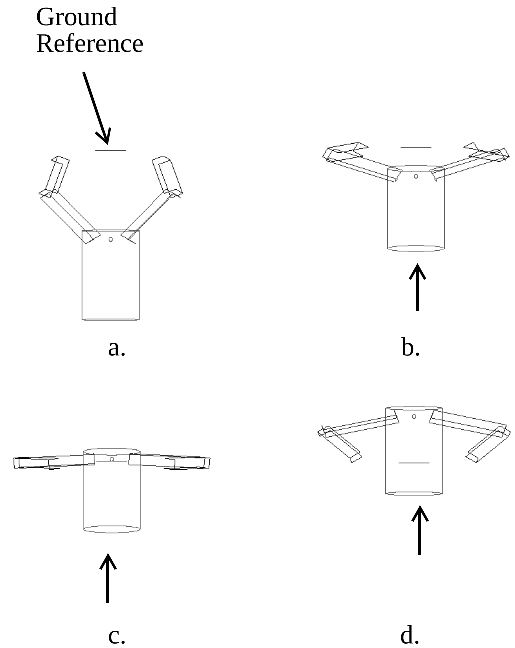

Figure 9: Simulation of an example swimming gait. (top view)

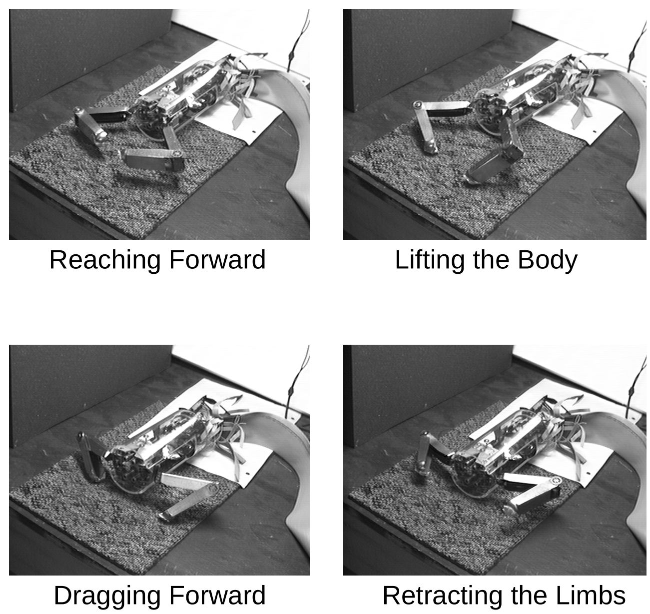

Figure 10: Implementation of a swimming gait on the prototype robot.

to two-armed swimming strokes. These are the "conventional" gaits, characterized by stances with the arms slightly splayed out to the sides and a full stride through much of the range of motion of the shoulder joints (Figure 9). To clarify operation on the target mechanism. Figure 10 contains a sequence of images of the TerminatorBot "swimming."

The narrow-passage gait is a novel gait that makes profitable use of the differential shoulder joint and unique ability of the first link to rotate around its principal axis. Motivated by the ability of mice, which can penetrate any opening through which they can pass their head, the robot can gain passage through openings that are no wider than the body itself (provided navigational capability is sufficiently precise). The motions of the limbs require zero lateral

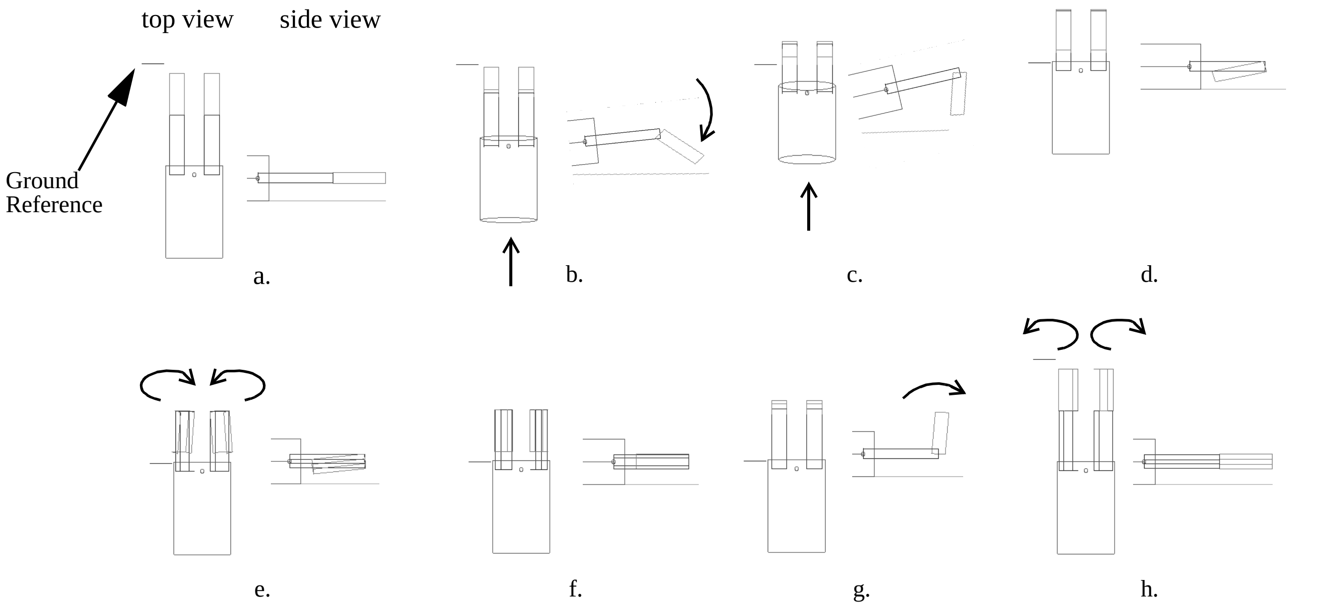

Figure 11: A narrow-passage gait. The robot’s arms start a stride outstretched in front of it. In a. through d. it pulls itself forward with the elbow joints, while in e. through d. it rotates the arms back into position to begin another stride. The end effector (claw) is not drawn, hence the space between the robot and the ground line.

clearance. (Although required vertical clearance is slightly larger than one body diameter.) Illustrated in Figure 11 with both top and side views, motion is effected entirely forward of the robot’s body as it pulls itself along. Again, Figure 12 illustrates the narrow-passage gait on the prototype.

The bumpy wheel gait is another novel gait that makes use of the ability of the differential shoulder to rotate 360 degrees. As Figure 13 indicates, the arms “roll” like broken wheels to move the body forward.This is the most powerful gait as all four shoulder motors are coupled to drive the body forward and forces on the elbow joint are absorbed by the structure. In fact, the current prototype does not have slip-ring electrical contacts, so continuous rolling of joint two is not permitted. Still, the bumpy wheel gait can be implemented by rolling 180 degrees, straightening the elbow, and rotating back to the start position.

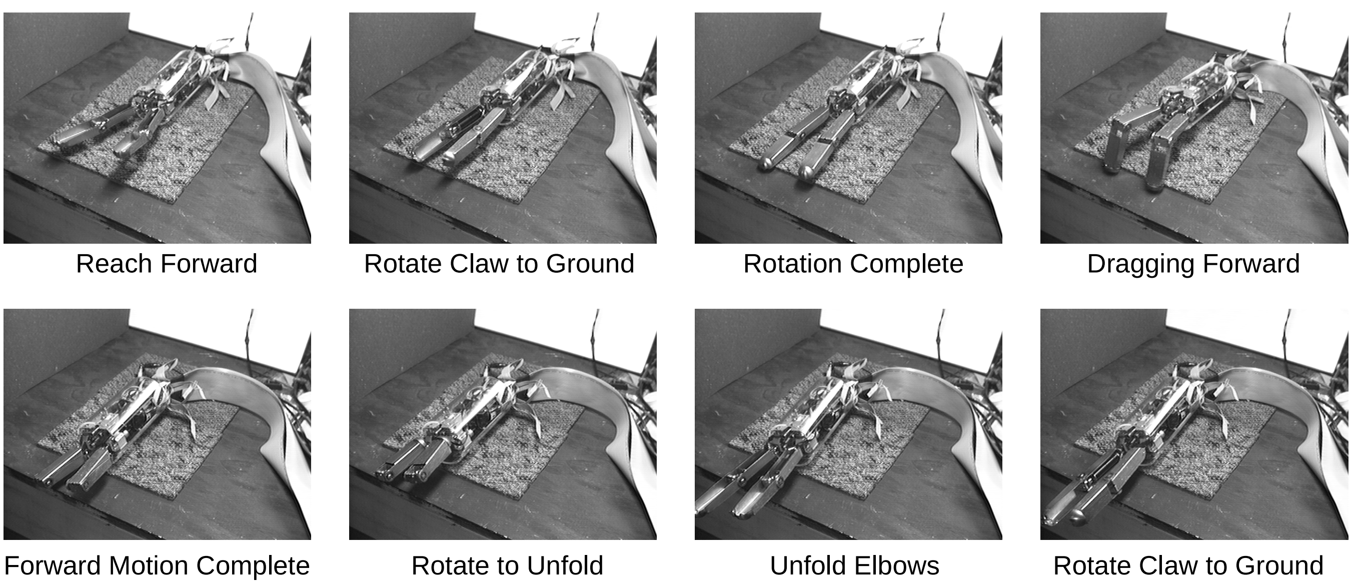

Figure 12: Implementation of the narrow-passage gait on the prototype robot.

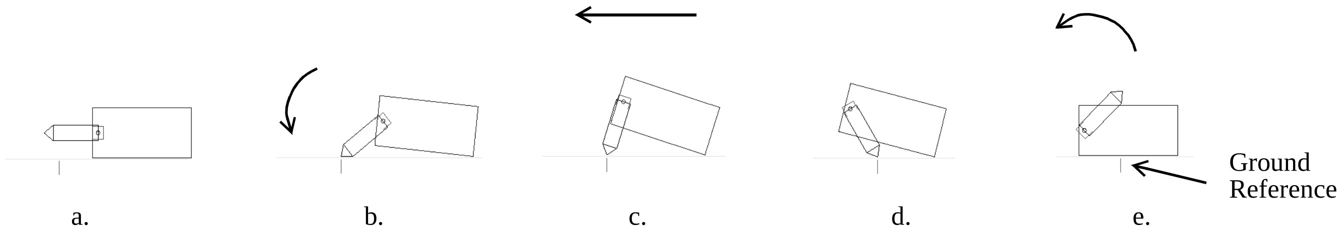

Figure 13: A bumpy wheel gait (side view). The torque of all four shoulder motors is coupled to produce forward motion (toward the left).

The body-roll gait is quite different from the others. Rather than being a kinematic approach to dragging the robot to its destination, this proposed locomotion gait uses dynamics and an assumption of a smooth, level surface. Since the arms can tuck inside the cylindrical form of the body, the “can” is able roll, once it gets going. The body-roll uses a single arm to build angular momentum by swinging it perpendicular to the roll axis. The other arm tries to prevent kick-back during the swinging motion. The swinging arm then folds up, into the body, causing a reactionary torque that rolls the body forward or backward. In order to effect turns, a swimming gait would most likely be used to reposition the body. The use of an accelerometer for gravity sensing would provide odometry.

The body-roll gait can be achieved using one arm, but one-arm gaits, in general, comprise a separate, distinct category of gaits that can be based on variations of the other gait classes. One use of these is to implement emergency homing measures in the event of an arm failure.

GAIT ADAPTATION

The focus of our adaptation studies is to develop intelligent agents that can detect changes in the performance of the locomotion gaits (and, eventually, manipulation “gaits”) and hypothesize-and-test modifications to improve performance. The agents will learn their own metrics of performance and how to tune them.

Our implementation of gait adaptation is based on the Port-Based Adaptable Agent Architecture (PB3A) from Carnegie Mellon University [16]. A Port-Based Agent (PBA) consists of a collection of Port-Based Modules (PBM) which are essentially port automata (much like the Port-Based Objects of the Chimera real-time operating system [17]). The architecture provides a standard wrapper supporting periodic and aperiodic execution, intercommunication, parametrization, and graphical display of PBMs.

The approach we are taking to implement a gait agent is to implement a series of underlying gait primitives as PBMs. These gait primitives will include tracking a joint-space trajectory segment, tracking a world-space trajectory segment, a guarded move, etc. A gait, then, will actually be a cyclic trajectory through the primitive space and a gait agent will maintain this cyclic behavior with appropriate additional PBMs for tuning the parameters of the primitives and measuring performance.

In many ways this resembles work on central pattern generators (CPG) [18], which are rhythmic, low-motor behaviors found in biological systems. But CPGs are cyclic open-loop actuation commands. The “CPG” in our gait agents would cycle through primitive space, not actuation potential space. This allows incorporation of both open-loop and closed-loop primitives at different stages of the cycle. Eventually, we hope this will allow the smooth transition from intensive closed-loop monitoring of a gait to predominantly open-loop control of a gait as the learning progresses. This phenomenon is generally observed in biological systems as an entity becomes more “skilled.”

SUMMARY

The design of the *TerminatorBot* was presented with examples of novel and conventional locomotion gaits. The mechanism employs dual-use limbs for both locomotion and manipulation to conserve space and functionality in a highly resource-constrained application.

It can be argued that the gaits presented are inefficient compared to wheels or even legs that are optimized for locomotion. This may be true. Dual-use generally implies non-optimal for both uses. The motivation behind this design is that both locomotion and manipulation are required to maximize utility of the robot as a whole, but size and ruggedness constraints prohibit redundant systems optimized for their specific purposes. In this sense, we are trying to optimize the robot as a whole, rather than specific parts.

The ultimate goal of this research is to develop self-adaptive software agents that intelligently manage gait behavior, analyzing changes in terrain conditions and adapting gaits to accommodate. While only a rough outline was presented of preliminary work that is still underway, we hope to minimize pre-compiled strategies in favor of self-developed tuning and measurement rules.

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