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

Richard M. Voyles

Dept. of Computer Science and Engineering
University of Minnesota
Minneapolis, MN 55455
voyles@cs.umn.edu

Abstract

A novel, miniature robot designed to use its two arms for both manipulation and locomotion is described. Intended for military and civilian surveillance and search-and-rescue applications, the robot must be small, rugged, and lightweight, hence the desire for dual-use. 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 two novel locomotion gaits and a third conventional gait.

1 Introduction

In the final scene of the movie Terminator, a fictitious humanoid robot loses its lower torso including the legs it uses for locomotion. In the research laboratory, the scene would be over as a swarm of graduate students attempt to salvage the tangled wreckage. In Hollywood, the robot dynamically reconfigures its locomotion strategy, employing its manipulators (arms) as locomotors to drag itself across the floor. Furthermore, it visually servos toward its intended target.

This type of dual use for manipulation/locomotion -- which is not uncommon in the biological world -- is our primary goal with *TerminatorBot*. We intend to produce a visually-servoed, two-armed robot that drags itself to visual landmarks and visually manipulates objects using the same two arms. Our motivation is provided by military special operations and civilian SWAT team applications in which very small, rugged, gun-launchable robots can be used for reconnaissance, surveillance, and search-and-rescue operations.

2 Prior Work

Mobile manipulation is an area of research that has not been extensively addressed in the robotics community. Manipulators have been placed on mobile robots before (in fact, commercial offerings from Nomadic Technologies and RWI include various “manipulators” as options, including PUMA robots), 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. [4]). Carriker, et al integrated the path planning of low-DoF subsystems, but motion operations and design for each were treated separately [1]. Khatib has done significant work in integrating the motion control of arms and mobile bases through the Operational Space formulation [3], but has not performed visual servoing 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 ([8] and [9], respectively) and PolyPod/PolyBot at Stanford/Xerox ([12]) are notable examples. SM^2 and DM^2 are symmetric, 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.

3 Target Applications

The TerminatorBot concept is an outgrowth of our work on the DARPA Distributed Robotics program to create a 40 mm diameter surveillance robot for eventual deployment by means of an M203 grenade launcher [11]. The entire system comprises a hierarchy of heterogeneous robots. At the bottom of the hierarchy are the 40 mm “Scouts” (Figure 1).

Figure 1: 40 mm diameter “Scout” mobile robot.

These are severely resource-constrained in terms of power, locomotion range, and payload capacity, hence the need for heterogeneity in functionality within its level of the hierarchy. Between levels of the hierarchy, there is also heterogeneity as the robots are distinguished according to size: physical size, battery size, and CPU size.

Next up in the hierarchy are the “Rangers.” They are based on RWI, Inc.’s ATRV Jr. robotic platform and provide medium-range mobility (on the order of a few kilometers) as well as communications and computational support for the Scouts. They carry a supply of Scouts and deploy them as necessary.

There is another level in the hierarchy for large-scale locomotion but it is irrelevant to the design and application of the Scout and/or TerminatorBot. (The TerminatorBot is an alternate design for the Scout level of the hierarchy.) Scouts possess two modes of locomotion: rolling and hopping. On smooth surfaces, two dense-foam drive wheels efficiently roll the robot along with minimal power consumption and a reasonable degree of navigational certainty. When encountering an obstacle (common for a robot only 40 mm tall) the Scout can winch in its foot and hop up to one meter in height. (Current versions can hop only 25 cm in height.)

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.

Still, its small size gives it stealth and the ability to access small spaces. This is primarily of interest to the military, but there are civilian uses, as well. For example, equipped with a camera or microphone (the payloads are interchangeable) 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. Of course, these are natural military applications, 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.”

With vibration detecting payloads, Scouts can be deployed along a roadside to discretely monitor traffic. They can hide nearby, monitoring for vibration signatures that would indicate heavy equipment or large troop movements. Finally, it has been suggested they could be used to carry small distributed explosive charges that can be amassed to sufficient volumes through their numerosity. This can serve for demolition of specific targets or detonation of land mines or other unexploded ordnance.

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 alternate designs. For example, the Scouts 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). 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 [10].

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 could be beneficial. This could provide camouflage during surveillance, additional access during search-and-rescue, and an alternate detonation means during de-mining.

4 Mechanism Design

The robot consists of a cylindrical body with two 3-degree-of-freedom (DoF) arms that can fully stow inside the body (Figure 2). The ultimate goal is to fit the 40mm diameter form factor of a launchable grenade, but the current prototype is approximately two times oversize with a diameter of 75 mm and maximum reach of each arm of 170 mm.

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.

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

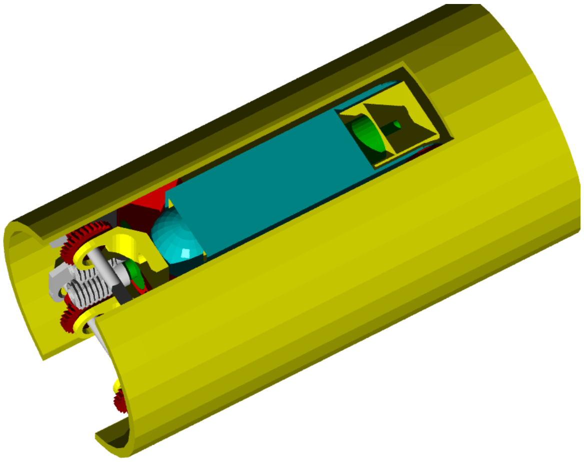

Figure 2: CAD rendering of TerminatorBot in the stowed configuration.

torque to a traditional 1-DoF elbow joint that drives the 70mm second link. Incorporated into the joint are torque sensors for direct measurement of joint torque at the point of application. Force/torque sensing is incorporated for use during manipulation of objects and also to enable servoed back-drivability of the gear train.

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 (see cross-section in

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

Figure 5) consists of four to eight radial flexures arranged with regular spacing about the center point [6]. 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 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. 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.

The use of strain gages on such a small device (The flexures are only 2 mm wide and 2.5 mm long) would

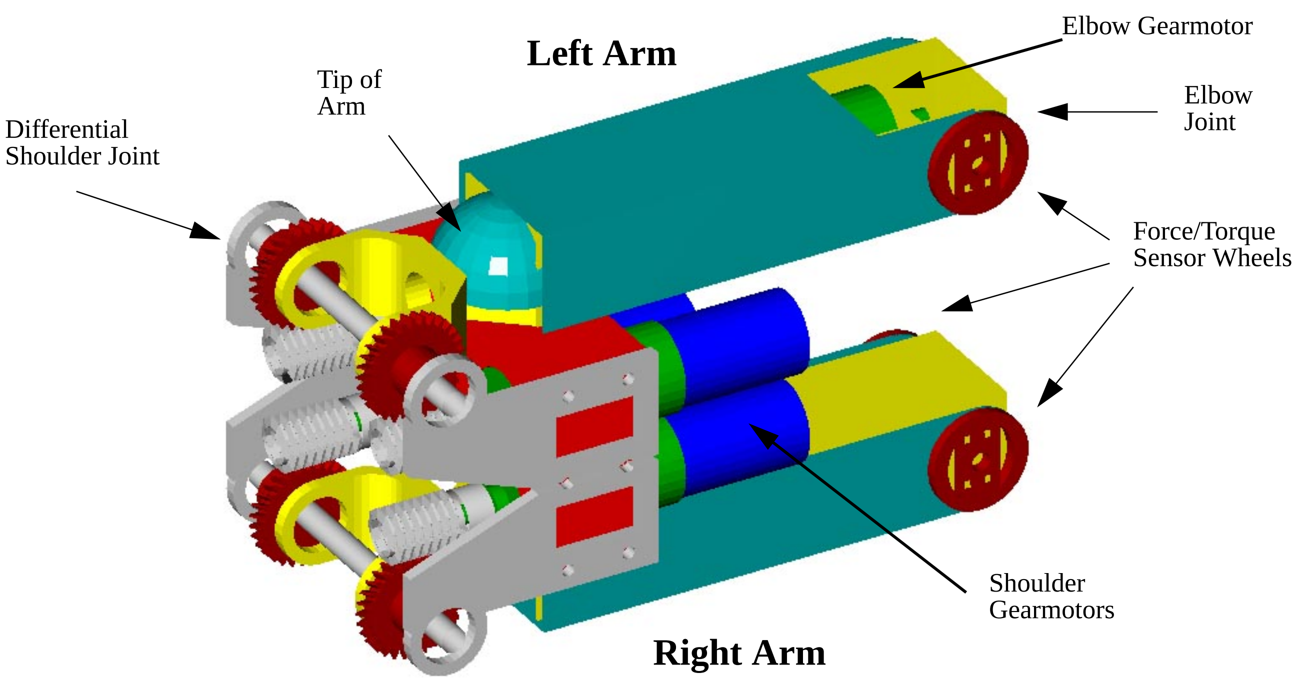

Figure 3: Internal parts of the TerminatorBot in the stowed configuration. Bearings and some other parts are not illustrated.

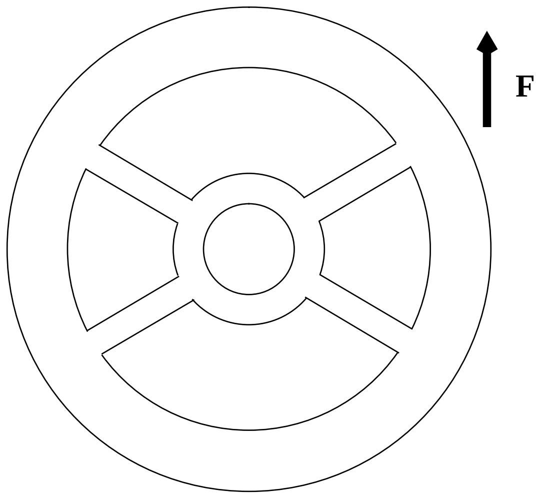

Figure 5: Cross-section of “traditional” torque sensor with radial flexures (although irregular flexure spacing is “non-traditional” - see text).

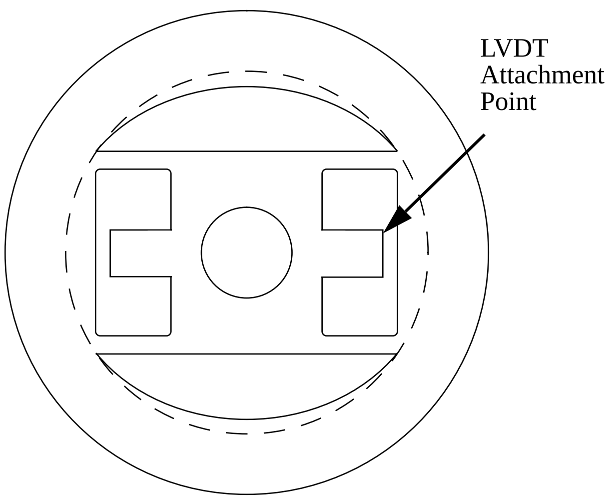

Figure 6: Cross-section of the force/torque sensor wheels used on TerminatorBot.

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 [2]. 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 sensable, 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.

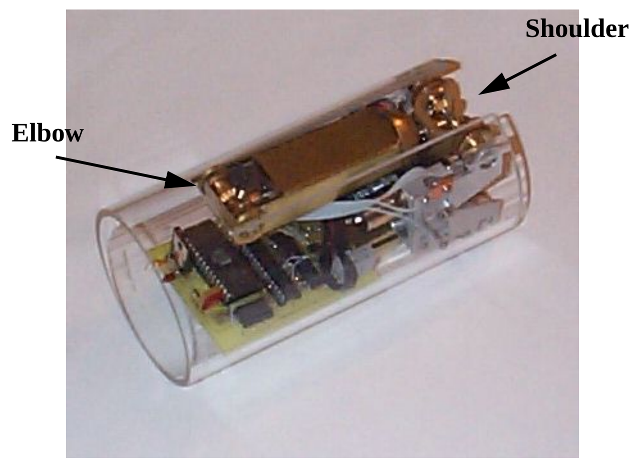

Figure 7: Assembled TerminatorBot in stowed configuration.

5 Locomotion Gaits

Novel mechanisms often suggest novel and mechanism-specific gaits, as was the case with PolyPod [12]. There are three proposed classes of locomotion gaits for use on TerminatorBot: swimming gaits, narrow-passage gaits, and bumpy-wheel gaits. All the gaits are used on dry land, but the “swimming gaits” are so named because of their similarity to human swimming strokes. These are the “expected” 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).

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. With this type of gait, the robot can gain passage through

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

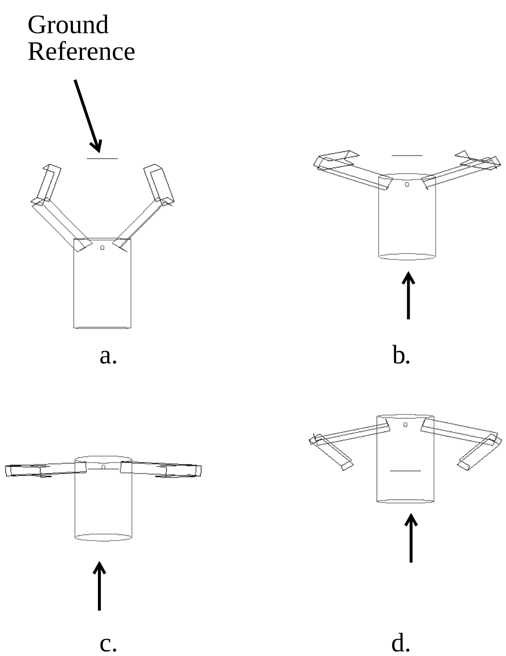

Figure 9: An example swimming gait. (top view)

openings that are no wider than the body itself (provided navigational capability is sufficiently precise). Illustrated in Figure 10 with both top and side views, motion is effected entirely forward of the robot's body as it pulls itself along.

Finally, the bumpy wheel gait is another novel gait that makes use of the ability of the differential shoulder to rotate 360 degrees. As Figure 11 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.

It can be argued that these gaits 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.

6 Acknowledgments

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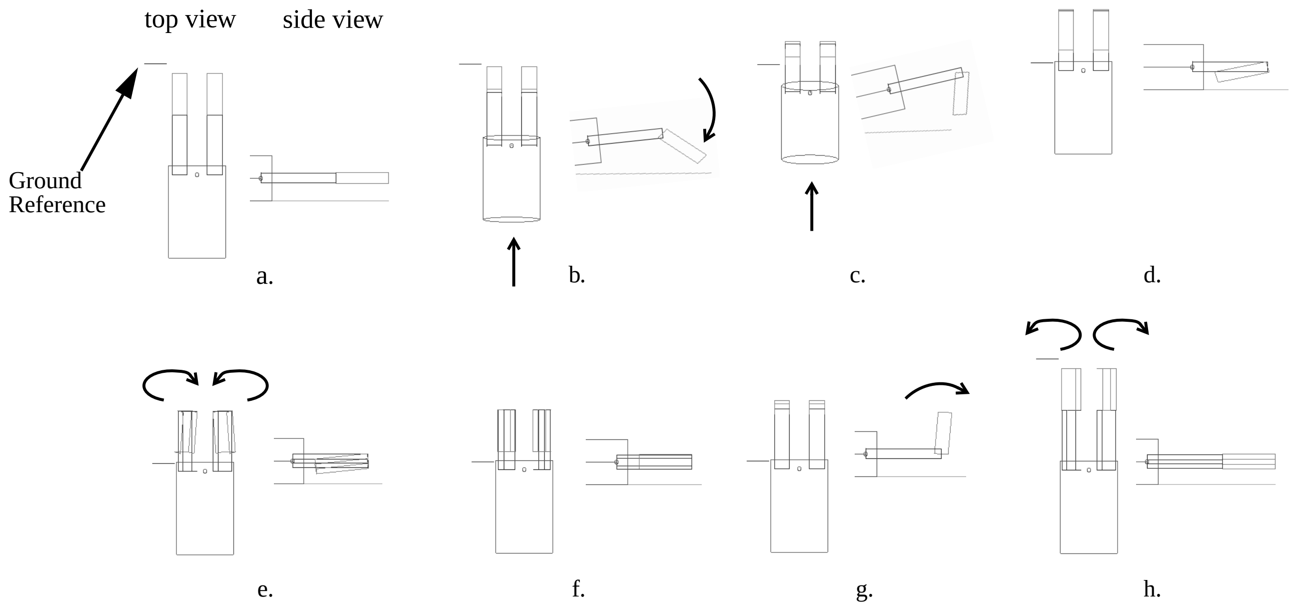

Figure 10: A narrow-passage gait. The robot's arms start a stride outstretched in front of it. In a. through d. it pulls itself forward with the elbow joints, while in e. through d. it rotates the arms back into position to begin another stride. The end effector (claw) is not drawn, hence the space between the robot and the ground line.

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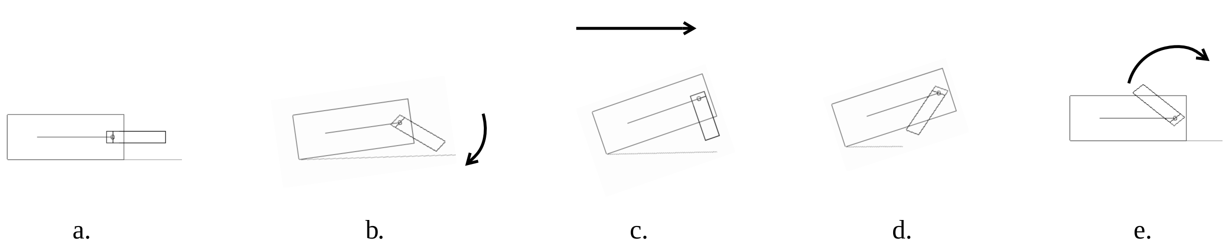

Figure 11: A bumpy wheel gait (side view). The torque of all four shoulder motors is coupled to produce forward motion (toward the right). Again, the claw is not drawn.