Core-Bored Search-and-Rescue Applications for an Agile Limbed Robot

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ABSTRACT

A custom version of the TerminatorBot is described for core-bored inspection during search-and-rescue operations. "Core-bored inspection" refers to visual inspection of a void by passing a small camera through an access hole into the void. This is the classic "camera-on-a-stick" approach. Sometimes the access hole occurs naturally. Sometimes a suspected void has no access hole. To gain access, a hole is bored through the rubble with a coring tool, hence the term "core-bored inspection." In either case, the camera, once inside, can articulate to look around, but is limited to line-of-sight. Occlusions can prevent a thorough inspection or force using/boring another hole. A small, agile robotic device could augment the use of such cameras. We propose the TerminatorBot as as a prototype limbed robot for studying such applications.

INTRODUCTION

Interest in robotic aids for urban search and rescue has skyrocketed within the research community in recent years [1] - [15]. These studies have included mechanisms, sensors and sensor processing, navigation and planning, field trials, and human/robot interaction.

The reasons for all this research activity are threefold. First of all, time is of the essence in search and rescue. The likelihood of survival drops off very rapidly after the first 48 hours of a serious incident and it normally takes up to 12 hours just to secure the site and set up a base for rescue operations. This leaves roughly 36 hours of operational time, so any tools that can safely increase the pace or amplify the personnel can yield huge benefits in human terms.

Secondly, the environments are extremely dangerous for both survivors and rescuers. The World Trade Center incident in 2001 as well as the Mexico City earthquake of 1985 both claimed the lives of hundreds of rescue workers. Any tools that remove the rescuers (including trained animals) from harm's way, while extending their reach, yields a double dividend. (The loss of a rescuer can lead to the loss of a survivor, as well.)

Finally, the problems are rich and challenging without an end-to-end solution of the autonomy problem. Search and rescue robots are teleoperated, yet the difficulties of sensor interpretation, planning, and locomoting in these highly disorienting environments are profound. Robots can be quite valuable in this domain without full autonomy.

This paper resulted directly from the experience of an NSF-sponsored workshop that paired robotics researchers with fully certified emergency responders in a live field exercise [14]. A public building, destined for demolition, was made to simulate a tornado disaster (Figure 1) while robotics researchers observed and participated in the rescue operations with robotic and conventional tools.

Figure 1: A partially demolished building provided the setting for a search and rescue training exercise as part of the NSF-sponsored workshop on "Rescue Robots for Research and Response."

One of these conventional tools used by FEMA (Federal Emergency Management Agency) emergency response teams (such as Indiana Task Force 1, an R4 participant) is the Searchcam [18]. The Searchcam 2000 is an extendable, articulated, video probe capable of reaching 2.5 meters into voids in a collapsed structure and swivelling 180 degrees to look for signs of life.

With only a 2.5-meter range (the "Super Probe" can reach 7 meters), it is clearly not designed to allow a rescue worker to stand outside a dangerous area at a safe distance to explore a remote collapsed structure. Instead, the most common use of the SearchCam is to poke into existing voids or quickly bore a hole in a structurally safe concrete slab -- such as a poured concrete floor or a fallen concrete wall -- to see if there is a void on the other side. In fact, it is not

Figure 2: The SearchCam 2000, demonstrated by a member of Indiana Task Force 1.

Figure 3: A member of Indiana Task Force 1, describing the operation of the concrete boring tool.

uncommon to bore through several such slabs that have fallen on top of each other or are leaning against each other in a “lean-to” fashion.

To facilitate such rapid exploration, another standard piece of FEMA emergency response equipment is a concrete boring tool with a variety of bit sizes that generally range up to about 100 mm in diameter. These tools can cut through several centimeters of un-reinforced concrete in several minutes and bit extensions allow boring up to a distance of two meters. Once the hole is bored (typically a 60-75 mm bit is used for the SearchCam), the SearchCam is inserted into the hole and the operator can look around the void for victims or survivors.

The problem with the SearchCam is it can only see line-of-sight. The tip of the telescoping boom is articulated with one degree-of-freedom. The articulation of the camera tip, coupled with rotating the boom of the camera, allows the operator to see in any direction from the bore hole. But, frequently, these voids are cluttered with debris and rubble and a single vantage point is not sufficient to examine all the areas that may be occluded from view. What is desirable in these cases is to lower an agile robot down into the void (or at whatever approach angle the access hole affords) to examine these occluded areas.

ALTERNATIVES

A compatible device to the Searchcam is the Cable Probe, also from Search Systems, Inc. [18]. The Cable Probe is a camera on a tether without the boom. While it could be lowered into a void deeper than the Searchcam, it has no means of reorienting its view, so it suffers from the same drawbacks in this scenario.

Currently available robotic vehicles, such as the PackBot and MicroVGTV (Figure 4), are too large to fit down a bored hole. In thin slabs (such as plaster or very thin concrete), it is possible to bore several holes adjacent to each other to create a slot through which a robot like the MicroVGTV can fit. (This was recently demonstrated, with much difficulty, by Indiana Task Force 1 during the NSF-sponsored joint training session: R4 - Rescue Robots for Rescue and Response.) The PackBot, on the other hand, is much too large even for this. And boring adjacent holes through many inches of concrete induces too much “wander” in the boring bit to maintain parallelism of the holes.

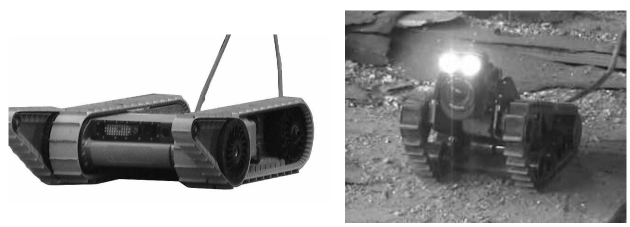

Figure 4: iRobot’s PackBot (left) and Inuktun’s MicroVGTV (right) are popular search-and-rescue robots, but neither can fit down holes bored by equipment carried by FEMA emergency response teams.

A COMPACT LIMBED ROBOT

Instead, a new robotic platform is required with very small size, yet high agility in highly-rubbled terrain. This robot must also have adequate robustness for rapid deployment. The TerminatorBot [16] (also known as the CRAWLER Scout for Cylindrical Robot for Autonomous Walking and Lifting during Emergency Response) is a prototype robot that has been developed as a demonstration platform for search-and-rescue operations. At about 73 mm in diameter, it is perfectly suited for dropping down a 75 mm bored hole. And because, at this scale, wheels would be of minimal value in a highly rubbled area, it uses limbs for crawling locomotion.

Figure 5: The TerminatorBot crawling through a simulated rubble field.

Current research with TerminatorBot has focused on gait development for basic locomotion [16], autonomous visual servoing toward areas of interest for reducing operator burden [13], automatic classification of terrain conditions [15], and 3-D identification of features in a rubbled landscape. These studies have been carried out with laboratory prototypes of the TerminatorBot that are tightly tethered to a host workstation for research flexibility (Figure 6).

Figure 6: An unwieldy tether system on research prototypes reduces deployability.

We have found a suitable site and have core bored a test hole to permit realistic simulations of actual void investigations with varying amounts of rubble. (See Figure 7.) The TerminatorBot can fold its arms completely inside the cylindrical shell that surrounds it, allowing it to

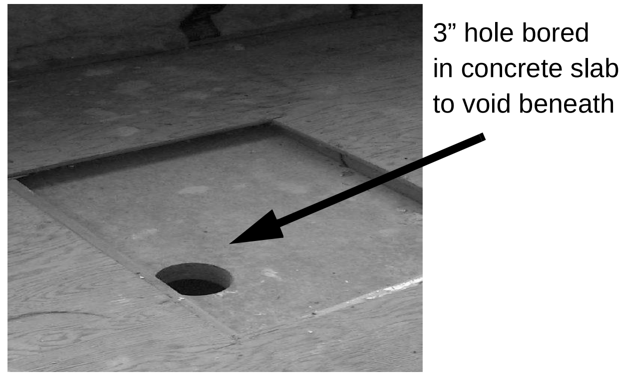

Figure 7: 75 mm hole bored through 25 cm concrete plank for simulating void investigation with TerminatorBot.

slip down the 75mm bore hole. This test site will be used for dropping down TerminatorBots, and, perhaps, other robots, such as the Scout [2], to investigate their usefulness for exploring voids (Figure 9).

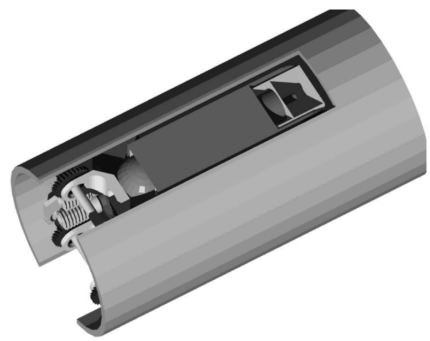

Figure 8: TerminatorBot in the stowed configuration for descending into the bore hole.

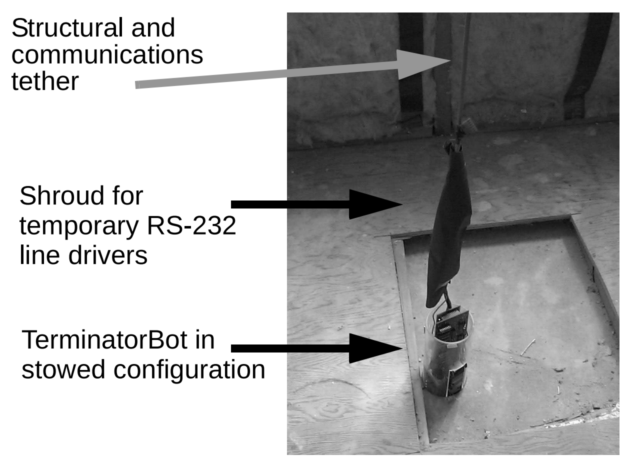

Figure 9: A TerminatorBot prototype with thin tether being lowered into the bored hole.

Once inside the simulated void, various rubbled surfaces can be tested for locomotive ability. Relatively benign rock and wood chip fields are illustrated in Figure 10. These robots are tested in a controlled laboratory environment for locomotive ability.

EMBEDDED MICROCONTROLLER

We are currently developing a variety of powerful on-board CPUs for autonomous operation of the TerminatorBot. But search-and-rescue work is still largely completed via teleoperation. Therefore, for the core-bored inspection version we have developed a simple, rugged, embedded microcontroller specifically for teleoperation. The CPU includes six channels of hardware encoder counters, six channels of three-amp capacity pulse width modulation (PWM) and a 2-g accelerometer for measuring body attitude.

The Atmel ATmega128 RISC microcontroller provides sufficient computational power to run a PID controller, trajectory interpolator, and serial command interpreter, as well as providing data logging for user display and post-mortem analysis.

To manage timing and real-time scheduling and task dispatching, we have ported a stripped-down version of the Chimera real-time operating system [19] to the Atmel chip. The implementation of *port-based objects* is actually non-preemptive, but allows for efficient implementation and scheduling of cooperative multi-tasking real-time objects with minimal RAM. The PID controller, trajectory generator, command interpreter, and log module are all spawned as port-based objects. (Port based objects are port automata with special methods to manage real-time operation.)

HUMAN/ROBOT INTERFACE

The human/computer interface design is critical for devices used under stressful conditions such as emergency

Figure 10: Benign rubble surfaces on a laboratory benchtop.

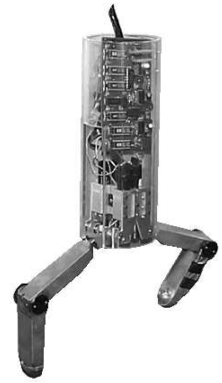

Figure 11: Core-bored search-and-rescue version of TerminatorBot with embedded microcontroller and thin tether.

response. In search-and-rescue, space is cramped and rugged, while users wear gloves, respirators, and hard hats. A bulky PC is impractical for most operations, particularly as an aid to the Searchcam, which has a single, small video display.

We have developed a multi-modal PDA-based interface that provides rich functionality for the researcher, but hides it behind a graphical point-and-move interface for novices. Since one of the main advantages of the mechanism is its ability to manipulate, there is a manipulation mode that displays a 3D wire frame model of the TerminatorBot and allows full configuration of the limbs by pointing the stylus. The need for precision in manipulation mode precludes a split screen (top and side views) for full 3D control of the end points. Instead, we are looking at innovative ways to display 3D information to the user with a 2D screen using height and differential cues around the periphery.

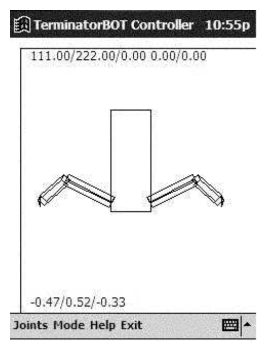

Figure 12: The graphical manipulation command mode of the PDA interface.

But manipulation mode is of limited use for a time-constrained urban search and rescue mission. Instead, the user just wants to drive around without being distracted by the high complexity (compared to wheeled and tracked vehicles) of the mechanism. Yet, because the robot is small and the environment highly rubbled, higher complexity may be needed to be effective. (Complexity is one of our points of study in developing this flexible research tool.) This complexity must be hidden from the user.

The locomotion interface provides the ability to drive around without being burdened too much by the complexity of the mechanism, yet full functionality is accessible.

Because locomotion involves cyclic motion of the limbs, the two icons are animated cartoons that reinforce the notion that the user is in locomotion mode. The top icon (top view of the TerminatorBot) has a steering direction control point that allows the user to steer the robot as it is moving forward. This control point also controls forward speed (like a joystick). The bottom icon (side view of the robot) has four control points for tuning the shape of the gait. Moving the control points changes the animation of the icons to give the user a hint of how her changes will affect the robot.

Selecting a different gait may present different parameters. The bumpy wheel gait is less configurable than the swimming gait. (The gaits are described in [16].)

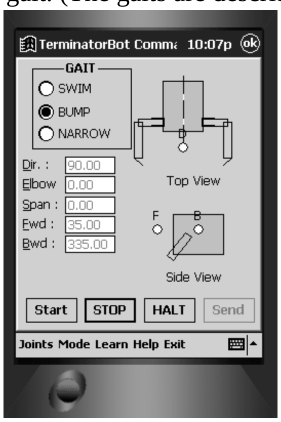

Figure 14: Locomotion panel for the bumpy wheel gait.

While pointing on a PDA screen is fine for researchers and user studies, it is impractical in a gloves-on environment. We are developing a simple “gestural joystick” based on magnets embedded in the gloves and magnetic field sensors embedded in the sleeve of the user.

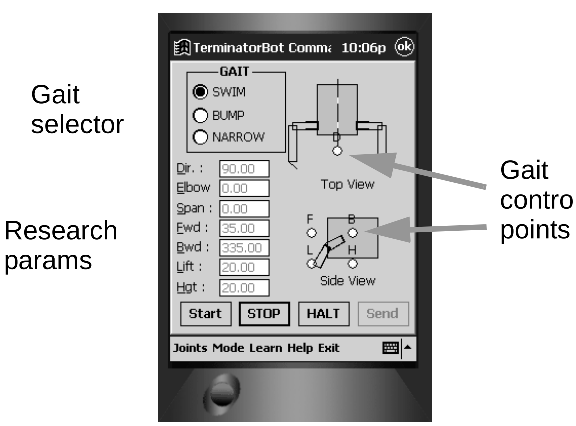

Figure 13: Locomotion panel for the swimming gait

Grabbing the sleeve at the wrist immobilizes both the sleeve and the user’s gesturing hand, while indicating to the robot that valid commands will begin streaming. Pointing the hand moves the cuff of the glove relative to the sleeve. The glove cuff carries magnets that are sensed by the sleeve. The motion of the hand relative to the sleeve will be converted into directional information by the PDA. These directional commands will then be sent to the robot, via the communication tether, to direct the motion of the robot. When the user releases her sleeve, the PDA ignores motions of the hand, allowing her to move about as necessary. The glove can be taken on and off at will because it is completely wireless and passive.

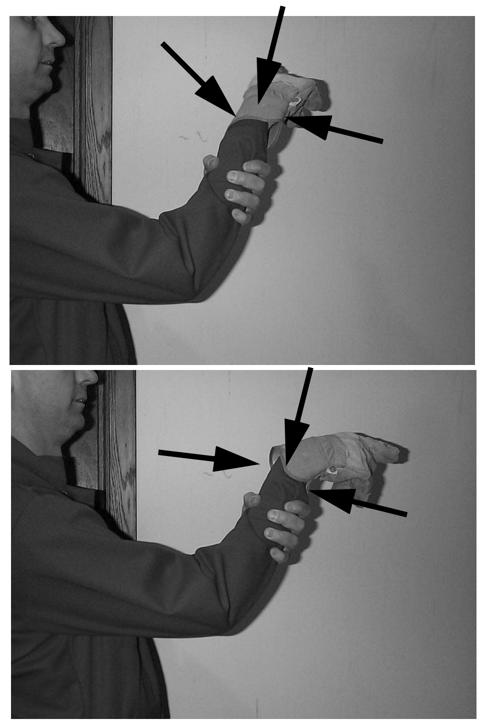

Figure 15: Pointing to the left (top) or straight ahead (bottom) moves the glove cuff (and magnets) with respect to the sleeve.

Mounting the glove apparatus on a universal joint and moving it through controlled angles yielded preliminary data. Figure 16 shows not only good separable functions but bad singularities if the magnet passes directly over a sensor (right ahdn plot).

It is important to reiterate that this is not a “data glove.” It does not measure the complex finger joint configurations of the hand as in [20]. It is simply a 2- or 3-DoF joystick constructed of the user’s wrist. (We are currently working on a 2-DoF, but 3-DoF is possible.)

Since the relationship between the glove and sleeve will vary each time the user grabs and releases her forearm, calibration is a tricky matter. We are applying our shape

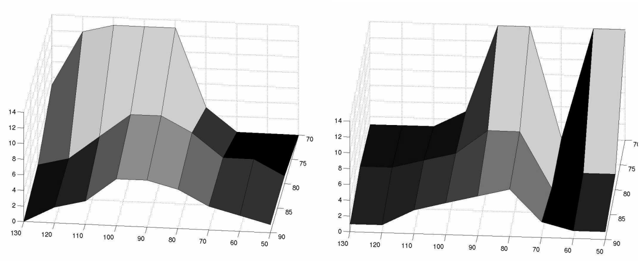

Figure 16: Surface profiles of two spatially distributed field sensors as the glove was rotated in left/right (x axis - degrees) and forward/back (y axis - degrees) directions. Z axis is magnetic field strength.

from motion self-calibration paradigm [17] to “lock-in” the intrinsic “shape” of the calibration matrix (which should remain invariant) and apply a transform based on the zero-point defined as the user grabs the forearm. Work on interpreting the signals from this gestural joystick is ongoing.

DISCUSSION

A custom version of the TerminatorBot was described for core-bored inspection as an aid to visual inspection with the Searchcam. This robot can fit into the same 75mm hole bored for the Searchcam but extends the range of inspection beyond line-of-sight from the bore hole. The robots have demonstrated the ability to locomote over rough terrain under teleoperation. Promising human/robot interfaces have been developed, but user studies have yet to be undertaken.

We expect this robot to be a rapid prototyping tool for experimenting with limbed core-bored inspection robots in the field.

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