Modular Reconfigurable Robots, An Approach To Urban Search and Rescue

Mark Yim, David G. Duff and Kimon Roufas

Xerox Palo Alto Research Center

3333 Coyote Hill Rd, Palo Alto, CA 94304

Abstract

Modular, self-reconfigurable robots show the promise of great versatility, robustness and low cost which are all elements for a successful urban search and rescue (USAR) system. This paper presents examples and issues in realizing those promises. PolyBot is a modular, self-reconfigurable system that is being used to explore the hardware reality of a robot with a large number of interchangeable modules with applications to USAR. PolyBot has demonstrated locomotion versatility over a variety of terrain and manipulation versatility with a variety of objects. PolyBot is the first robot to demonstrate sequentially two topologically distinct locomotion modes by self-reconfiguration. PolyBot has raised issues regarding software scalability and hardware dependency and will continue to raise issues as the design evolves to resolve preceding issues and explore the potential of modular, self-reconfigurable robots. Finally this paper addresses the issues required to make robot systems useful for current USAR applications.

1. Introduction

In the past two decades it is estimated that disasters are responsible for about 3 million deaths worldwide, 800 million people adversely affected, and property damage exceeding US$50 billion. The recent earthquake in Turkey in November of 1999 left 700 dead and 5000 injured. Many of these deaths were from structural collapse as buildings fell down onto people.

Urban Search and Rescue involves the location, rescue (extrication), and initial medical stabilization of victims trapped in confined spaces. Voids formed when a buildings collapse is one instance of a confined space.

Urban Search and Rescue may be needed for a variety of situations, including earthquakes, hurricanes, tornadoes, floods, fires, terrorist activities, and hazardous materials (hazmat) accidents.

Currently, a typical search and rescue team is composed of about ten people, including canine handlers and dogs, a paramedic, a structural engineer, and various specialists in handling special equipment to find and extract a victim. Current state of the art search equipment includes search cameras and listening devices. Search cameras are usually video cameras mounted on some device like a pole that can be inserted into gaps and holes to look for signs of people. Figure 1 shows a device being used. Often a hole is bored into the obstructing walls if a void is suspected to exist on the other side. Thermal imaging is also used. This is especially useful in finding warm bodies that have been coated with dust and debris effectively camouflaging the victim. The listening devices are highly sensitive microphones that can listen for a person who may be moving or attempting to respond to rescuers calls. This whole process can take many hours to search one building. If a person is found extrication can take even longer.

Figure 1: A firefighter (with white hat) views the portable screen of a search cam which is probing below a concrete slab.

Small robots may be used to aid in the search and rescue effort. [1]. A small highly mobile robot may be able to more easily and rapidly explore voids deep in a rubble pile that the equipment and dogs cannot detect. The highest priority for rescuers in a rescue operation is the safety of everyone, especially the rescuers. Collapsed structures are often unstable and dynamic. Further collapse may be imminent, especially in the case of earthquakes that can be followed by aftershocks. A robot remotely searching an unstable structure allows the searcher to be effective at a safer distance.

It is interesting to note that USAR operations during typical disasters more often recover dead bodies than live ones. While live rescues are the primary goal, the rapid recovery of dead bodies is also valuable to the surviving relatives and is often important in some cultures. However, if there is any risk of harm to the rescuers, this recovery will not be attempted. A robot system may enable the rapid recovery of deceased victims as well without risk to the rescuer.

Several robot systems have been proposed to aid in search and rescue however these systems have not yet been deployed to generic rescue personnel. [1][2][11].

Another USAR application that has received little attention is the rescue of victims in a trench collapse. This is not usually the result of a major disaster like an earthquake, rather these collapses occur while workmen are digging or fixing pipes or other underground equipment. Because this is more mundane, it receives less press, however the frequency of this accident is much higher. Small robots that can go through sewer pipes or other underground conduits may be able to find victims. Small robots that can dig may also be able to find victims more readily.

This paper presents the developments of a modular robot system towards USAR applications as well as the issues that would need to be addressed in order to make such a system practical.

2. N-Modular robot systems

Modular robotic systems are those systems that are composed of modules that can be disconnected and reconnected in different arrangements to form a new system enabling new functionalities. There have been a variety of modular reconfigurable systems as there are many aspects of robot systems that can be modular and reconfigurable. These include

- Manual reconfiguration [13] vs. automatic reconfiguration [6]
- Homogenous [9] vs. heterogenous modules [6]

The systems addressed here are automatically reconfiguring, hardware systems that tend to be more homogenous than heterogenous. This last phrase means that the system may have different types of modules but the ratio of the number of module types to the total number of modules is low. Systems with all of these characteristics are called *n-modular* where *n* refers to the number of module types and *n* is small typically one or two, (e.g. a system with two types of modules is called 2-modular). The general philosophy is to simplify the design and construction of components while enhancing functionality and versatility through larger numbers of modules. Thus, the low heterogeneity of the system is a design leverage point getting more functionality for a given amount of design. The analog in architecture is the building of a cathedral from many simple bricks. In nature, the analog is complex organisms like mammals, which have billions of cells, but only hundreds of cell types.

Modular *self-reconfigurable* robot systems can also reconfigure (re-arrange) their own modules. There are a growing number of modular reconfigurable robotic systems that fit the n-modular profile [7][9][10][12][14][15][17][19]. These systems claim to have many desirable properties including versatility (from many configurations), robustness (through redundancy and self-repair) and low cost (from batch fabrication). However the practical application outside of research has yet to be seen. While the number of modules has been large in simulation, the physical implementation of these systems has rarely had more than 10 modules. Section 2 explores these desirable properties while Section 3 examines some of the issues that need to be addressed before n-modular systems with large numbers of modules can be made practical. Section 4 presents the PolyBot system design, an overview of the functionality already demonstrated, and finally some programming strategies.

2.1 Motivation

Modular reconfigurable robotic systems that are composed of many modules have three promises. They promise to be versatile, robust, and low cost [6][9][12][16]. These promises serve as the primary motivation for studying this work.

2.1.1 Versatility

Modular reconfigurable robots with many modules have the ability to form a large variety of shapes with large numbers of degrees of freedom (DOF). The robot may change its shape to suit different environments. In this fashion the robot is very versatile. For USAR, the same system could do a variety of tasks. A robot could start in the shape of a snake to slither through small cracks and holes and pipes to find a victim. Once the robot has reached a live victim, the robot can supply a remote communications medium to and from the victim which is often essential to the psyche of the victim as well as possibly providing important situational information to the rescuers. In addition to being highly mobile, the versatility of the system allows it to achieve other tasks in the highly constrained environment such as shoring the structure near a victim. An air hose may also be brought to the victim to provide ventilation in the confined area both to provide oxygen to breathe as well as removal of possible toxic or flammable gases.

In many extrications, shoring is an integral part. If the unstable material cannot be removed from above the victim (for example if a person is trapped on the lower floors of an unstable multi-story building,) the ceilings and walls need to be shored to prevent further collapse before rescuers can attempt to reach the victim.

One measure of the versatility of a modular system may be the number of isomorphic configurations that are capable by a given system [4]. For many systems, this number grows exponentially with the number of modules. Another measure may be the number of DOF in the system. This also grows with the number of modules though linearly in this case.

2.1.2 Reliability

Another result of being modular and reconfigurable is the ability of the system to repair itself [9]. When a system has many identical modules and one fails, any module can replace it. Another factor increasing the reliability is that a module's area of influence is typically local. If one module is not working properly, since it can only affect things locally, the errors it introduces may be able to be compensated by the modules around it. Basically there are redundant modules that can either compensate or replace failing modules. As the number of modules increases, the redundancy also increases. This may be critical in unstable environments.

2.1.3 Low Expense

As the numbers of repeated modules increases, the economies of scale come into play and the per-module cost goes down. Again, increasing the numbers of modules enhances this effect. On the other hand, the total number of modules still increases. The question of exactly which factor effects the total cost of the system the most is difficult to predict without implementing a full system to determine the components needed and their relative costs.

2.2 Issues in Realization

The three promises listed above have several issues that need to be addressed before these systems hold these properties.

2.2.1 Versatility

While larger numbers of modules may result in more configurations and DOF, it is not clear that large numbers of modules will lead to increased versatility. Even if many configurations and motions are possible, systems must have methods for planning and controlling the motion to take advantage of these configurations. Computational time complexities in planning and control often grow exponentially with the number of modules. In most cases, the computational resources also grow, though linearly, with the number of modules as each module often carries some computational resource itself. For the promise of versatility to come to fruition, methods of exploiting the distributed computational resource and strategies for dealing with the exponential size of many of the spaces will need to be developed.

N-modular systems have the possibility of being very versatile, both from the large numbers of DOF and the large numbers of possible configurations. However, the capability to do a specific task does not necessarily make it reasonable to use the technology for that task. It is usually the case that tools made specifically for a task are cheaper and more efficient at that specific task than the versatile tools capable of doing many different tasks. For example, a set of pliers can be used for tightening a bolt as well as many other things, however, a box wrench specifically designed for that bolt will work more reliably (with less chance of stripping the head) and be cheaper.

A key set of applications in which the n-modular systems excel are those in which versatility is critical. Typically, these are situations in which some information about the environment is not known a priori. Thus, a system cannot be designed specifically for a task, since the task that is needed is not known. Search and rescue is one such application. The environments are not known a priori and are highly unstructured. Thus, the optimal shape of a robot, whether it is like a snake to crawl through things, or a spider to more quickly climb up structures is not known.

2.2.2 Reliability

Having many modules and large redundancy does not necessarily increase the robustness of the system. More modules mean that there are more modules that can fail. If a system has millions of modules, it is very likely that many of them will not be working properly. Given a module type that has a probability $\boldsymbol{p}$ that it will fail after a given amount of time $\boldsymbol{t}$, the probability of at least one module failing in a system after time $\boldsymbol{t}$ with $\boldsymbol{n}$ modules is $[1-(1-\boldsymbol{p})^{\boldsymbol{n}}]$ which approaches probability 1.0 for large $\boldsymbol{n}$.

To take advantage of systems with large numbers of modules, it is critical that these systems have the appropriate control strategies to compensate for failing modules. The least reliable control strategy would be dependent on every module performing correctly for the success of a task (e.g. a chain is only as reliable as its weakest link). To employ compensation requires the understanding of the failure modes of the modules and the construction of algorithms, configurations and designs tolerant to failure of some percentage of the modules.

There are two basic strategies to increase robustness to failing modules. The first is to use the redundancy of a system and global feedback to compensate for local errors of individual modules. The classical feedback control view would be that the failed module inserts some disturbance into the system and the global control of the system compensates for the introduced error. The second strategy is sometimes called self-repair [6][9]. In some instances, it may be appropriate to eject a failed module (detach it) from the system and replace it with a working module from a non-critical position. If a module is failing in such a way that the ability to detach is also lost, the working modules that are attached directly to the failed module may "sacrifice themselves" by detaching themselves carrying the failed module away.

2.2.3 Value

One of the general tenets of the modular reconfigurable approach is that versatility comes from the programming of the devices. Hence, rather than developing unique hardware and then programming it for a given robotic task, the problem is instead reduced to (re)programming the existing versatile hardware. The broad utility of this method will require the development of programming tools to facilitate and simplify programming.

As the flexible automation industry discovered in the 1980's, the cost of programming (and reprogramming) systems is often more than the cost of the hardware, thus reducing the value of the flexible nature of the hardware. The extreme versatility of n-modular systems requires a new paradigm in programming.

3. PolyBot

PolyBot uses two types of modules, segments and nodes. The segments have only one DOF which is a rotational one. In addition, a shape memory alloy (SMA) actuator based latching mechanism has been integrated on the system.

3.1 PolyBot design

The design philosophy behind PolyBot is that each module is very simple and that by itself cannot do very much, however in combination with many others a more complex system can be built to achieve more complex tasks. Another design goal for PolyBot is that each module should fit within a cube 5cm on a side.

Two PolyBot systems have been built and experimented with. The first is a simple quickly made prototype with hobby RC servos and off-board computation. The structure was built using laser-cut acrylic parts. Up to 32 modules were bolted together and controlled via gait control tables with off board computing. This system will not be described any further in favor of the second system.

The second system is newer and is pictured in Figure 2. The segment module can be divided into three subsystems: 1) structure and actuation, 2) sensing, computation and communication, and 3) connection plate and is shown in Figure 3.

3.1.1 Structure and actuation

The structure is made of laser-cut stainless steel sheet and is basically cube shaped. Two opposing faces of the cube have connection plates. The module's one DOF allows these two faces to be rotated so they are no longer parallel. They can be rotated up to +90 or – 90 degrees. A brushless DC motor with a 4 stage 134:1 gear reduction sits in the middle of the segment on the axis of rotation. The gear reduction consumes the most space. The motor protrudes outside the 5cm cube desired size limit. In future versions, a form of harmonic drive will reduce the gear box space allowing the motor to sit within the size constraints

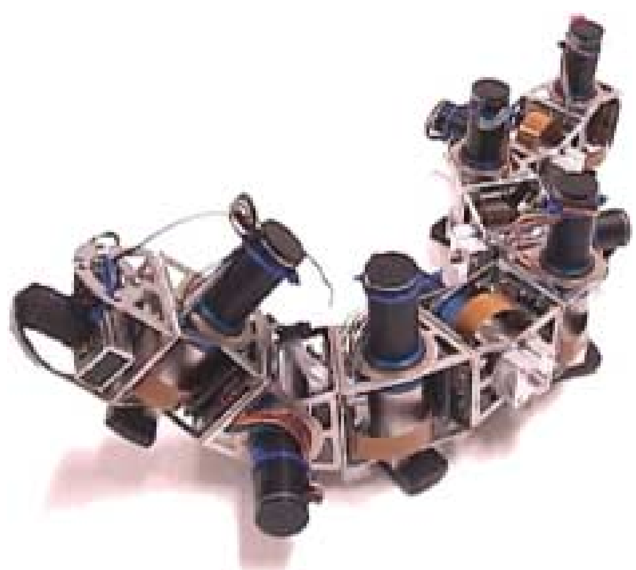

Figure 2: Nine new modules attached together in a snake configuration. A micro video camera/transmitter with 9V battery is attached at the front.

3.1.2 Sensing, computation and communication

Each module contains a Motorola PowerPC 555 embedded processor with 1 Megabyte of external RAM. This is a relatively powerful processor to have on every module and its full processing power has not yet been utilized. The final goal of full autonomy may require the use of these processors and memory.

Currently, the sensing is limited to hall-effect sensors built into the brushless DC motors serving both for commutation as well as encoder position with a resolution of 0.45 degrees. It is planned to include proximity, tactile, force/torque sensing and possibly a low-resolution CMOS chip-camera on each module.

Each module communicates over a semi-global bus using the (controller area network) CANbus standard. Two

CANbuses on each module allows the chaining of multiple module groups to communicate without running into bus address space limitations.

3.1.3 Connection Plate

Each segment has two connection plates. The connection plate serves two purposes. One is to attach two modules physically together. The other is to attach two modules electrically together as both power and communications are passed from module to module.

PolyBot allows two connection plates to mate in 90 degree increments allowing two modules to act together in-plane or out-of-plane. This multi-way attachment requires the electrical connectors to be both hermaphroditic as well as 4 times redundant.

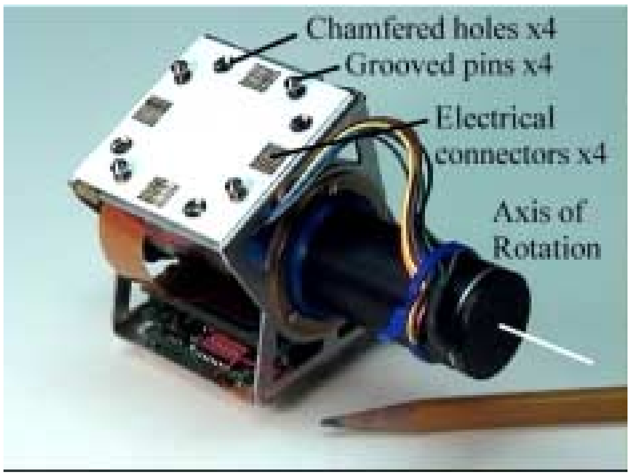

Figure 3: One module showing the connection plate with 4 pins, 4 mating chamfered holes and 4 hermaphroditic electrical connector sets.

These connectors were custom made as no commercial hermaphroditic connectors could be found with large enough current capacity and high enough density (1mm pitch). The connection plate consists of 4 pins along with 4 chamfered holes as shown in Figure 3. An SMA actuator rotates a latching plate that catches the 4 pins from a mating connection plate.

Each connection plate has 2 photo-diodes and 4 LED's that are sequenced to allow the determination of the relative 6 DOF position and orientation of a mating plate. This will aid in the closed loop docking of two modules and their connection plates.

3.1.4 Node

The node is a rigid cube made of 6 connection plates (one for each face. It serves two purposes; one is to allow for non-serial chains/ parallel structures, the other is to house higher power computation and power supplies. Portable power is very difficult to incorporate into modular systems, so PolyBot currently runs tethered to a power supply.

3.2 Locomotion and Manipulation Versatility

PolyBot has demonstrated that n-modular systems can be very versatile by showing multiple modes of locomotion with a variety of characteristics that may be advantageous for different USAR operations. Most of these have been implemented on the physical robot and some are shown here in simulation. In addition, they have demonstrated some manipulation as well.

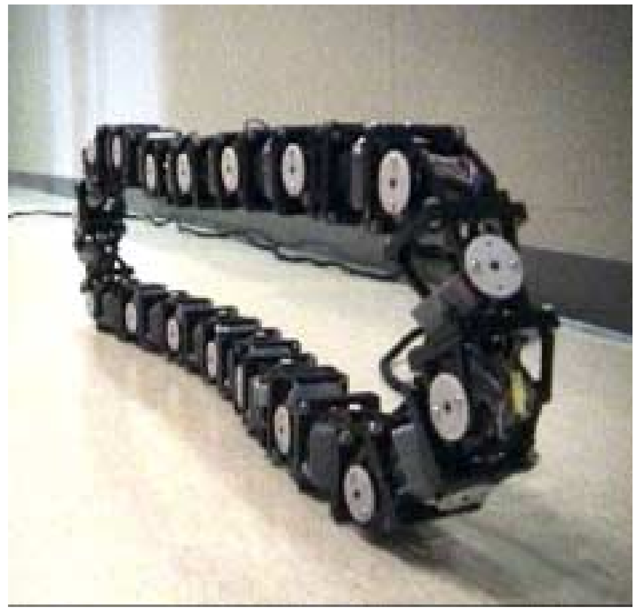

Figure 4: A loop of 32 modules using a rolling track locomotion.

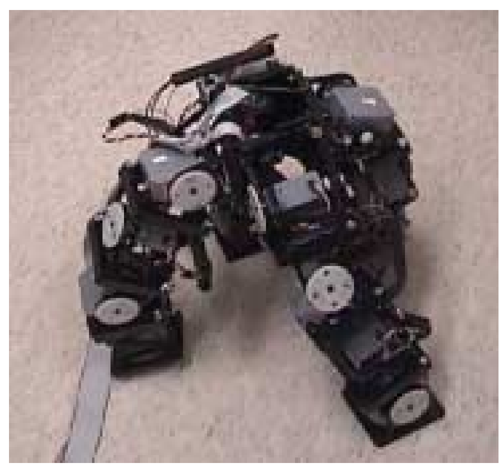

Figure 5: A four legged spider-like configuration.

The following gaits have been implemented include gaits that resemble

- Earthworm locomotion.
- Sinusoid snake-like locomotion, turning and straight as in Figure 2.
- a rolling track as in Figure 4.
- three-legged caterpillar-like locomotion,

- a 3 x 4 array of cilia-like locomotion/manipulation,
- a 6 legged locomotion (using a tripod gait),
- a 3-segment slinky-like tumbling locomotion,
- a 4 legged spider-like locomotion as in Figure 5.

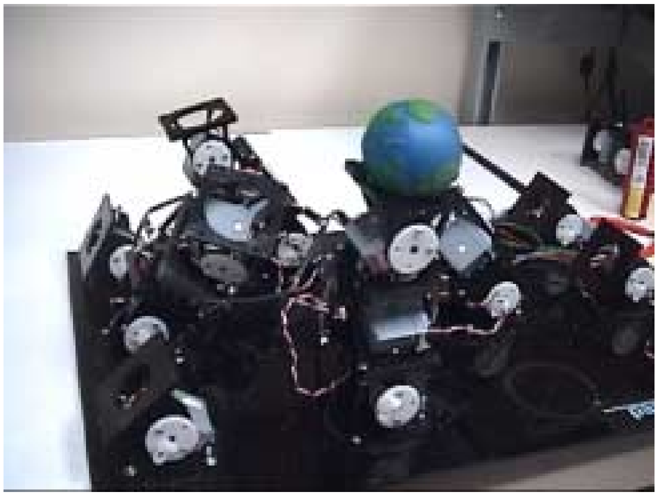

Figure 6: Four arms with three degrees of freedom each, demonstrate passing a small ball from arm to arm.

The sinusoid snake-like locomotion was demonstrated to work over a variety of obstacles including crawling in 4" diameter aluminum ducting pipes, up ramps (up to 30 degrees), over chicken wire, climbing 1.75" steps, over loose debris and wooden pallets as in Figure 7. This gait and the earthworm gait are perhaps the most useful during searches through tightly confined areas as they are the most mobile in terms of crossing obstacles such as holes ditches steps, under or between obstacles etc. [18].

The rolling track gait is the most efficient and the fastest gait over flat terrain. If there are large areas that need to be crossed quickly, for example a parking lot that has a hazardous chemical spill on it, this gait may be ideal.

With the appropriate planning and actuation, the spider gait may be able to climb up structures, although climbing has not yet been implemented.

Since locomotion is essentially a dual of manipulation, many of the legged gaits were demonstrated to show manipulation of objects. In addition multi-arm manipulation was demonstrated as illustrated in Figure 6. Manipulation would be useful in the digging out of victims. Extricating a person and even accessing deeper into a rubble pile is done by removing debris from the top of the pile and placing it in a cleared location to be sure that the pile does not collapse again endangering both the victim and rescuers. This involves not only picking up the debris but transporting it. PolyBot can use the distributed manipulation scheme to move debris down a chain of modules in a bucket brigade fashion.

Figure 7: Sinusoid gait moving through rubble (10 cm pipe)

3.3 Polybot Self-Reconfiguration Demonstration

PolyBot is the first system (in October 1998) to demonstrate two topologically distinct locomotion modes sequentially by self-reconfiguration. That is reconfiguration from using a loop gait (Figure 4) into a serial chain subsequently using a snake sinusoid gait. Later a demonstration, using 24 of the modules pictured in Figure 2, of the snake transforming into a spider was shown with teleoperated reconfiguration. This last transition was accomplished by attaching the two ends of the snake to the middle forming a figure eight. Then detaching the middle of the loops of the figure eight to form a 4 legged spider.

3.4 Programming strategies

Programming the motion of n-modular systems with large numbers of modules can be difficult. Planning the self-collision-free motions can be difficult as the size of this space is exponential in the number of modules, $\boldsymbol{n}$ ($\boldsymbol{n}$ is proportional to the number of DOF) [8]. In fact, determining when self-collision will occur is difficult to do in real time for many modules, as the number of point-to-point checks is proportional to $\boldsymbol{n}^2$. The inverse kinematics of serial chains with large $\boldsymbol{n}$ is also non-trivial as is the forward kinematics for parallel chains [5]. Adding the additional constraints of torque limits, joint limits and stability under gravity, the problem becomes impractical to solve optimally for the general case and even non-optimally in real-time.

It has been shown that precomputed gait control tables were an effective way to control large numbers of modules [18]. In fact, gait control tables controlled all of the implementations listed in Section 4.2. This method can be extended to be used for reconfiguration. Decomposing a structure into well-known "sub-structures" which have precomputed motions for reconfiguration is one approach [3]; another is called tree inversion [20].

For many applications, a fixed set of configurations is sufficient. In this case, reconfigurations can be pre-planned off-line between every member of the set and stored in a table. In fact, configurations in the fixed set may be chosen specifically for ease of reconfiguration.

The cellular nature of PolyBot and perhaps all n-modular systems lend themselves to hierarchies. Since the systems are already made up of many components that are in some sense divisible, it is easy to group the modules into larger virtual modules. These virtual modules can then also be grouped and a hierarchy formed.

4. Practical Issues in Robotics for USAR

Fully autonomous robots finding and rescuing victims will not happen in the near future as the technologies required do not yet exist. However, robot systems that are used in conjunction with existing USAR personnel is more likely. In order to develop a system that can be used by generic USAR personnel in real rescue situations, many issues need to be addressed.

A key aspect in the usefulness of these systems is the ability to not only detect that a live victim exists in a rubble pile to but to precisely locate that victim relative to the rescuers. In a typical scenario in which an actively used building has collapsed, it is fairly obvious that there are people inside. The key is to know where they are so that rescuers can extricate them safely. Unfortunately, this task is not easy. Standard localization methods such as GPS do not work well in the presence of metal structure such as concrete-rebar and other building material. Standard robotics line-of-sight localization methods clearly won’t work either.

These systems must be extremely robust. Firemen (the typical USAR personnel) are notorious for pushing the limits of equipment. The environment that this equipment is used in is the polar opposite from a research lab setting. The personnel may have their life at stake and have no time to delicately handle fragile equipment. In addition, extreme heat, moisture and dust are other typical environmental characteristics encountered.

For the generic USAR team, the system must be cost-effective. Many high-tech instruments exist today that are simply too expensive to afford.

In some instances, flammable gases are present or can collect in the confined spaces that a victim is trapped in. For this reason, most of the electrical equipment used by USAR personnel have an “intrinsically safe rating” which rates whether they will ignite an area filled with flammable gas. Having an actuation method and electronics, which do not spark, would be advantageous for these situations. In many typical USAR situations however, the typical sources of flammable gas (methane and propane) have been shut off and vented away during the early stages of a USAR operation, before the void search operations would occur. Never the less, having sensors that could detect gases would be prudent.

5. Conclusions and Future Work

There are three promises of modular reconfigurable systems; versatility, robustness and low cost. To implement systems that realize these promises and that can then be used in USAR applications is not trivial. As the number of modules scales up, it is not clear that these properties will even exist. PolyBot is one system that is being constructed that will explore these issues by building 200 modules, an order of magnitude more than has yet been attempted. PolyBot has already shown versatility in a variety of locomotion and manipulation tasks that lead toward USAR application, however reconfiguration is not yet autonomous. The implementation of reconfiguration will further explore autonomous versatility as well as robustness and self-repair.

While teleoperation is a valid approach for control in USAR scenarios, relieving constant supervision through limited autonomy will allow rescue workers to more effectively and efficiently use the system as well as possibly utilize multiple robot systems. By the end of 2000 the project will demonstrate 200 modules under teleoperated control. The goal for PolyBot in 2001 is to show 200 modules using robust autonomous locomotion, manipulation, and reconfiguration.

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