

# Modularity in small distributed robots

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## ABSTRACT

This paper describes the development of small mobile robots for collaborative surveillance tasks. Each of the robots, called Millibots, has only limited sensing, computation, and communication capabilities. However, by collaborating with other robots, they can still perform useful tasks. The task that we are considering is collaborative mapping and exploration inside buildings. To guarantee accessibility through narrow passageways (e.g. air ducts), the robots are very small, approximately 6x6x6cm. This size puts severe weight and power limitations on the design of the robots. To overcome these limitations, we are developing a modular system in which modules with different sensing, computation, and communication capabilities can be combined into a complete robot that is specifically designed for a given task. By making the design modular, we can avoid carrying around capabilities that are not essential for the current task. The concept of modularity also plays an important role in the design of the robot team. Here the “modules” are the individual robots and the design task addresses the problem of determining how many robots to use and what kind of capabilities to select on different robots such that the overall team is capable of completing its task. The paper addresses these design issues and illustrates them with the specific example of the Millibot team.

**Keywords:** Modularity, distributed robotics, robot collaboration, mapping, occupancy grid method.

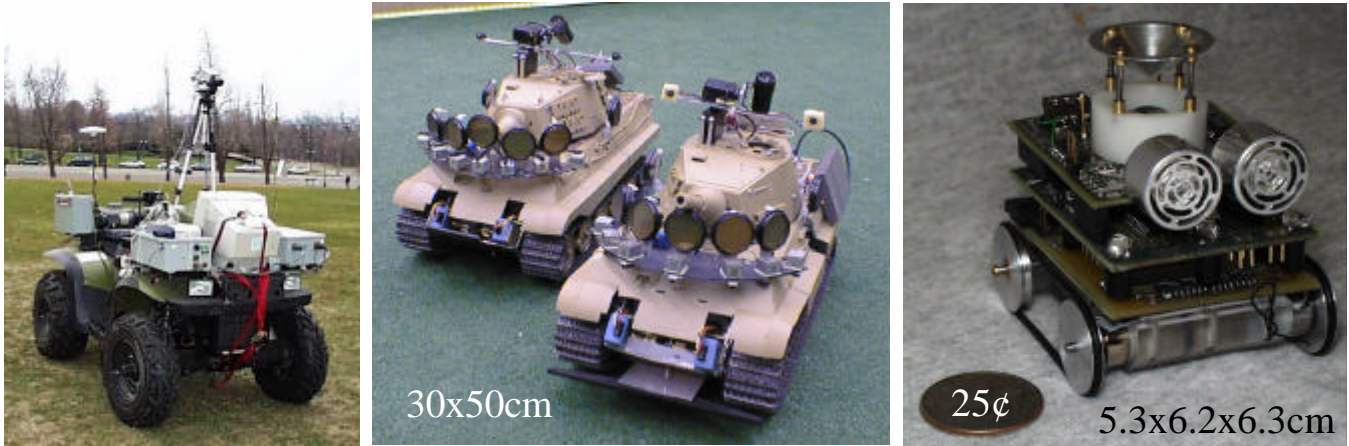
## 1. INTRODUCTION

In recent years there has been an increasing interest in distributed robotic systems<sup>1,2,3,4</sup>. In such a system, a task is not completed by a single robot but instead by a team of collaborating robots. Team members may exchange sensor information, may help each other to scale obstacles, or may collaborate to manipulate heavy objects.

A team of robots has distinct advantages over single robots with respect to actuation as well as sensing. When manipulating or carrying large objects, the load can be distributed over several robots so that each robot can be built much smaller, lighter, and less expensive. As for sensing, a team of robots can perceive its environment from multiple disparate viewpoints. A single robot, on the other hand, can only sense its environment from a single viewpoint, even when it is equipped with a large array of different sensing modalities. There are many tasks for which distributed viewpoints are advantageous: surveillance, monitoring, demining, plume detection, etc.

Distributed robotic systems require a new design philosophy. Traditional robots are designed with a broad array of capabilities (sensing, actuation, communication, and computation). Often, the designers will even add redundant components to avoid system failure from a single fault. The resulting systems are large, complex, and expensive. For robot teams, the design can be approached from a completely different angle, namely: "Build simple inexpensive robots with limited capabilities that can accomplish the goal reliably through cooperation." Each individual robot may not be very capable, but as a team they can still accomplish useful tasks. This results in less expensive robots that are easier to maintain and debug. Moreover, since each robot is expendable, reliability can be obtained in numbers; that is, if a single robot fails, only limited capabilities are lost, and the team can still continue the task with remaining robots.

Because the size of a robot determines to a large extent its capabilities, we are developing a hierarchical robot team. As is shown in Figure 1, the team consists of large All Terrain Vehicles (ATVs)<sup>5,6</sup>, medium-sized tank-like robots (based on a remote control Tamiya tank model)<sup>7</sup>, and centimeter scale Millibots (6x6x6cm). The ATVs have a range of up to 100 miles.



**Figure 1: A hierarchical team of robots consisting of ATVs, medium size robots, and Millibots.**

They are capable of transporting a user with multiple smaller robots to the area of interest. Once the team has arrived, the ATV with its multiple Pentiums can serve as a main processing node for high-level planning. It may control and coordinate multiple mid-sized robots each of which in turn heads a team of Millibots. Such a hierarchical organization allows us to combine the autonomy and computation power of the large ATVs with the distributed sensing capabilities of a large number of covertly operating Millibots. To take full advantage of the distributed sensing capabilities of Millibot teams, it is important that these robots be inexpensive, lightweight, and small. Small and lightweight robots can be easily carried by their larger counterparts higher-up in the robot hierarchy. They can maneuver through small openings and into tight corners to observe areas that are not accessible to larger robots. Small robots are also less noticeable allowing for covert operations in hostile territory. By building them inexpensively, they can be deployed in large numbers to achieve dense sensing coverage, adaptability at the team level, and fault tolerance.

To achieve both small size and expansive capabilities, we are developing Millibots capable of carrying specialized platforms. Instead of equipping every robot with every sensor, computation, or communication capability, we are building robots that are each specialized for a particular aspect of the task.

In one type of scenario, the robot team may be composed of robots with various range and position sensors but only limited computation capabilities. In this case these robots act as distributed sensor platforms remotely controlled by a team leader who performs the high-level planning. In another task, the same group of Millibots may be equipped with computational modules that provide local processing of data. The choice of platforms is dependent only on the task.

To achieve this level of specialization without the need for a huge repository of robots, we have chosen to develop the Millibots in a modular fashion. Each of the subsystems (computation, communication, sensors, and mobility) has been implemented as a self-contained module that can be configured with other modules to obtain a Millibot that is specifically designed for the given task.

The idea of modular and reconfigurable components is not new in robotics<sup>8,9,10,11</sup>. As early as the eighties several research prototypes of modular manipulator systems were developed. At Carnegie Mellon University, Paredis et al.<sup>12</sup> have developed the Reconfigurable Modular Manipulator System or RMMS that consists of a stock of link and joint modules of different sizes and specifications. The modules can be assembled into a wide variety of robot manipulators with different kinematic and dynamic characteristics. They also addressed the problem of task-based design,<sup>13</sup> that is: Which modular configuration should be used to obtain a manipulator that is optimally suited for a given task? A similar problem will have to be addressed for teams of distributed robots, namely: Which robots should be part of the team and which capabilities (hardware and software) should they have to accomplish this task? However, this complicated problem is outside the scope of this paper.

## 2. THE MILLIBOTS

The Millibots are small mobile robots with limited capabilities. Yet, by collaborating with each other as a team, they are able to accomplish important tasks such as mapping and exploration. To provide this utility, Millibots can be equipped with a full range of subsystems including computation, communications and sensing. In this section we start by exploring the motivations of building robots on a small scale. We examine some previous work in this area and discuss where Millibots

diverge. We continue with a discussion on the limitations of power and how a group can become more power efficient by adopting a heterogeneous nature. Finally we discuss the architecture and design of the various sub-modules and how they are integrated to produce a complete robot.

## 2.1. Size and power considerations

The primary factors that determine what a robot can do are size and power. The most obvious advantage of a smaller robot is that it can access spaces restricted by its larger counterparts. Small robots can crawl through pipes, inspect collapsed buildings, or hide in small inconspicuous spaces. For surveillance and exploration tasks, this increased accessibility dramatically impacts the overall functionality of the robots. However, with the small size also come the disadvantages of limited mobility range, limited energy availability, and possibly reduced sensing, communication and computation ability.

Our approach to overcoming these disadvantages is based on *specialization* and *collaboration*. To increase the mobility range of small robots, they can be carried to a particular deployment location by larger robots on the team. These larger robots can also serve as proxy-communication and proxy-computation nodes to communicate with the user over larger distances and to perform high-level planning and coordination tasks. Another possibility would be to have specialized small robots perform these tasks. For instance, a small robot may be specialized in communication, carrying two radio links, one for local communication with other small robots in its vicinity, another more powerful one for communication with the user. Specialization can also be used to provide a wide range of sensing capabilities to small robots. Different robots may carry different sensor payloads, such as a camera, sonar, or chemical sniffers. By sharing the sensor data with each other, the team as a whole can obtain a better image of the environment than can be achieved by a single large robot.

Though smaller robots can access areas unreachable by their larger counterparts, they are simultaneously limited by obstacles previously considered trivial. For example, a small robot may be able to access tight areas such as an air vent but become totally ineffective when climbing stairs. However, just as a group of cooperating robots can pool information to extend their utility beyond a single robot, multiple robots could come together to overcome physical obstacles. One of the avenues being explored by the Millibot group is mobility platforms that will allow a group of robots to dock with each other like a train in which all robots collaborate to push the lead robot over an obstacle.

The last significant issue facing robots on this scale is power. Current battery technology significantly limits the amount of energy that can be carried by a small robot. Alternate forms of energy sources are under development but have not yet proven viable at this scale. Currently, the Millibots are powered by two 3.2volt NiMH batteries that are capable of delivering a run time of about 90 minutes. NiMH batteries were chosen primarily because they are safe and easy to charge and provide an acceptable energy density. NiMH batteries also do not suffer from a memory problem allowing them to be recharged at any time during their run cycle.

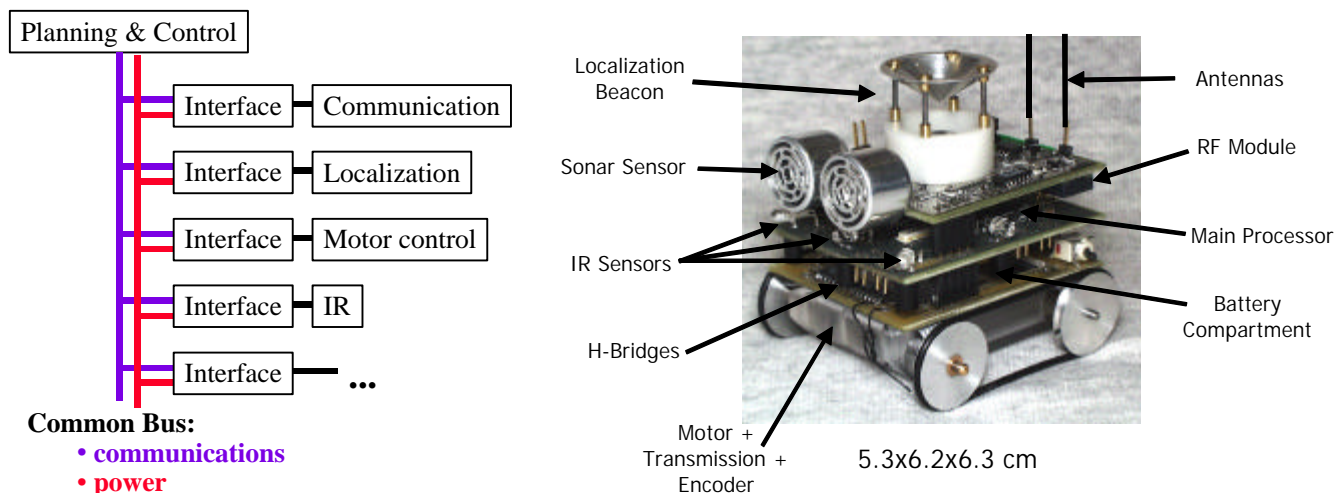
## 2.2. Modular architecture

As pointed out in the previous section, robot specialization is one way to build small robots that still have sufficient capabilities to perform useful tasks. One can assemble a team that consists of robots with specifically those capabilities that are required for a given task. By omitting the capabilities that are unnecessary in a particular task scenario, one can significantly reduce power, volume, and weight requirements. However, specialization has the disadvantage that many different robots need to be available to address the specific requirements of a given task.

To attain robot specialization without creating an unacceptably large pool of robots, we are building the Millibots in a modular fashion. Modularity allows one to assemble a large variety of robots from a small number of modular components

As is shown in Figure 2, each Millibot is composed of a main processor with optional communication and sensor modules housed on a mobility platform. The modules interface with each other through a standardized bus for power and inter-module communication. Each module contains its own microprocessor that implements the inter-module communication protocol and performs low-level signal processing functions for sensor and actuator control.

We are considering two different implementations of inter-module communications. Currently, each main processor provides a set of dedicated slots that are capable of servicing up to six sensor or actuator modules. Each module is assigned slots on the main processor in which timing and information are shared. The choice of module and slot is made by the operator and configured in software. All information is passed back and forth in the form of serial communications. A second possible implementation that we are adopting for future generations of the Millibots is based on I<sup>2</sup>C<sup>14</sup>. I<sup>2</sup>C is a bus design and communications protocol that allows multiple modules to be connected to a common two-wire bus. One wire provides a high speed, synchronous clock while the other provides a two way data line. All messages on the data line are pre-appended with



**Figure 2: The Millibot's architecture and subsystems.**

an address header identifying the target module. This interface is less restrictive than the dedicated slot method because it allows more modules to be connected to the same processor without having to designate separate pins.

### 2.3. The Millibot subsystems

Once the interface between the main processor and its modules has been defined, the necessary sub-systems can be iterated. Currently the Millibots can be composed from a suite of seven subsystems: the main processor module, a communication module, an IR obstacle detection module, two types of sonar modules, a motor control module, and a localization module.

Communications is essential in a coordinated team. Without explicit communications, a robot can only interact with team members using its sensors (e.g. vision-based “follow the leader” behavior)<sup>15,2</sup>. However, collaborative mapping and exploration requires the exchange of detailed and abstract information that cannot be easily conveyed implicitly. Therefore, to provide two-way communications within the group, each Millibot is equipped with a radio frequency transmitter and receiver. These units can exchange data at 4800 bps at a distance of up to 100 meters. The choice of units is based primarily on size and power considerations. We expect that smaller more powerful transmission units will become commercially available in the future as miniaturization in solid state progresses.

To perceive the world, a robot must have sensors. There are currently three sensor modules available to each Millibot. The first is a set of ultrasonic sonar modules that provide focused range information about obstacles. One sonar module type provides short range distance information for obstacles between 1cm and 0.6m. The second module type provides longer range information for obstacles between 0.15m and 1.8m. The short-range sensor module is ideal for Millibots that have to work in tight or cluttered areas. The long-range sensors are more effective in environments that are more open such as hallways or open office spaces. Because of the size of the sonar detector compared to the robot, Millibots can support only one sonar unit per robot. For some tasks, it may be desirable to have both short and long-range sonar sensing available. This can still be achieved by equipping some Millibots on the team with short-range and some with long-range sonar modules.

A potential complication with sonar sensors is the interference with sonar modules on other robots. Most sonar elements operate at a fixed frequency determined by their mechanical construction. Therefore, two robots using ultrasonic sensors in the same area may cause interference for each other. To provide continuous rudimentary obstacle detection, a Millibot may opt to carry an infrared proximity module. The proximity module provides an array of five infrared emitter-detector pairs that trigger when an obstacle intrudes within its cone of emission. The proximity elements can be calibrated to provide readings of up to 0.25m. Although the proximity detectors cannot be reliably used for range determination of objects, they can be used very effectively in conjunction with a sonar detector module. The proximity module can be continuously sensing an area around the robot. Upon detection of an object by the proximity detector, the sonar modules can be coordinated carefully to determine a better range measurement.

In some cases, the mission itself may dictate which sensors are needed to achieve a given task. Millibots support the addition of sensor modules that may not be directly used by the robot itself. The temperature module is an example of a unit which is strictly a distributed sensor. This module samples the ambient temperature around the Millibot, comparing it to internal settings and producing an alarm when conditions are exceeded. Like other modules, it is capable of being configured and

calibrated via the serial connection with the main processor. Any similar module can act as a mission payload as long as it does not violate the size and power constraints of the Millibots and provides a serial interface for data exchange. Sensor modules of this type include chemical sensors, radiation monitors, magnetic field detectors, and sound analyzers.

Except under the most controlled conditions, the sensors discussed so far cannot provide enough detail to resolve many of the problems facing a real robot. Real situations are fraught with anomalies. A method is needed to provide high bandwidth information during a mission for analysis by a higher level process or operator. To provide this service, Millibots can be equipped with a camera module. The camera module provides an external mini camera, video transmitter and power circuitry. Currently because of the limited processing capabilities of the Millibot, little if any of the video signal can be processed on-board. A small video transmitter is included with the module to transmit the raw video signal to an external processor or remote viewing station. Though not used by the Millibot, the camera module includes circuitry that allows the camera and its transmitter to be switched on and off via control signals from the Millibot. Control of the camera aids in effective power management. The camera need only be powered when an image is desired. The ability to remotely power down an individual transmitter also allows multiple robots to carry similar camera modules while using the same transmitter frequency. Interference is prevented by powering only one transmitter at a time. Additionally resources are minimized since only one receiving station and associated monitoring device is needed per Millibot group. However, though the camera module provides valuable visual information, it operates on the threshold of the Millibot's power budget. The current camera dissipates about 1.5 Watts of power. Due to the limited size of the battery, this type of sensor cannot be used continuously like other sensor packages.

Modularity provides flexibility in both construction and data flow. Each module in the Millibot arsenal is capable of being added to any system implementing the serial interface. This implies that some of the larger Millibots may contain multiple control processors each addressing a set of sensor modules. One such utility may be a Millibot that is designed to carry a second, non-mobile unit. Both robots may share common resources such as power or communications but act as separate logical entities in terms of the system control. Another implication is that some sensor modules may act as interfaces to other sensor modules. This would provide the ability to configure a system in a hierarchical fashion. A proximity module could receive commands from a central processor while producing control signals to a motor control module. This type of system is similar in operation to Brooks' subsumptive architecture<sup>15</sup>.

Not all scenarios will support robots designed with the same modes of propulsion. For example, a small robot equipped with a set of rubber tracks will perform well on a flat, slippery surface, such as a floor or table. However, it may perform poorly on a shaggy rug. Conversely, the same robot may outperform a robot equipped with wheels in another scenario. In the Millibot group, modularity has been extended to the mobility platforms as well. A mobility platform is selected for a particular Millibot and the main processor and its set of support sensors is added to make it a robot. In most cases, the mobility platforms will utilize a similar set of dc motors. Therefore, the same motor control module can be utilized and only the software needs to be changed. For those platforms that differ, they need only to include their own motor control module and define the software interface. Currently the Millibots have implemented only two sets of platforms both utilizing skid steering. Some Millibots are equipped with a plastic tread design which is ideal for rough surfaces like rugs while others are equipped with a rubber tread design which allows it to crawl up smooth inclined surfaces. Designs are underway to provide additional platforms, perhaps with feet or claws, that will allow a robot to climb small obstacles such as air vent joints or to collaborate to push each other over similar obstacles.

### **3. THE MILLIBOT LOCALIZATION SYSTEM**

For distributed robotic applications that require robots to share sensor information (e.g. mapping, surveillance, etc.) it is critical to know the position and orientation of the robots with respect to each other. Without knowing the position and orientation of the sensors, it becomes impossible to interpret the sensor data in a global frame of reference and integrate it with the data coming from other robots. Moreover, the Millibots require position knowledge to move to predetermined locations, avoid known obstacles, or reposition themselves for maximum sensor efficiency.

Conventional localization systems do not offer a viable solution for Millibots. Many robotic systems rely on Global Positioning Systems (GPS) and compass for determining their position and orientation in a global frame of reference<sup>16</sup>. However, due to its size, limited accuracy, and satellite visibility requirements, GPS is not appropriate for the small Millibots that operate mostly indoors. Dead reckoning, another common localization method, generally suffers from accuracy problems due to integration errors and wheel slippage<sup>17</sup>. This is even more pronounced for Millibots that rely on skid steering for which track slippage is inherent to the steering mechanism. Conversely, other localization systems that are based on landmark recognition<sup>18,14</sup> or map-based positioning<sup>20</sup> require too much computing power and sensing accuracy to be implemented on Millibots.

To overcome the problems encountered in the implementation of existing localization methods for a team of Millibots, we have developed a novel method that combines aspects of GPS, land-mark based localization, and dead reckoning<sup>21</sup>. The method uses synchronized ultrasound pulses to measure the distances between all the robots on a team and then determines the relative positions of the robots through trilateration. Similar systems have been developed<sup>22</sup> and are even commercially available (e.g. through IS Robotics). However, they are both too large and too expensive for operation on Millibots. Moreover, the system described in this paper is more flexible because it does not require any fixed beacons with known positions, which is an important relaxation of the requirements when mapping and exploring unknown environments.

The Millibot localization system is based on the trilateration,<sup>17</sup> i.e., determination of the position based on distance measurements to known landmarks or beacons<sup>23,24</sup>. GPS is an example of a trilateration system; the position of a GPS unit on earth is calculated from distance measurements to satellites in space. Similarly the Millibot localization system determines the position of each robot based on distance measurements to stationary robots with known positions.

The Millibot localization system uses ultrasound pulses to measure the distances between robots. We designed a localization module that can serve either as a beacon or as a localization sensor. Initially, at least three Millibots serve as beacons, while the remaining robots are configured as receivers. Periodically, each beacon simultaneously emits a radio frequency (RF) pulse and an ultrasonic pulse. As is illustrated in Figure 3, The RF pulse, traveling at the speed of light ( $3 \cdot 10^8$  m/s), arrives at all receivers almost instantaneously. The ultrasonic pulse, on the other hand, traveling only at 343 m/s (assuming 20°C air temperature) arrives at the receiver delayed by a time proportional to its distance to the beacon. Each Millibot measures this delay, using the RF pulse for synchronization, and converts it to a distance measurement by multiplying with the speed of sound. A team leader coordinates the pinging sequence to ensure that beacon signals from multiple robots do not interfere with one another.

After all the beacons finish pinging, every Millibot has a set of distance measurements from its current position to each beacon position. This information is sequentially transmitted to the host computer, which determines the actual position of every Millibot using an Extended Kalman Filter (EKF). In the future, we plan to calculate the Millibot positions on the local processor of each Millibot. However, currently the processor does not have the necessary computation power to perform these floating-point computations.

To produce and detect beacon signals, each Millibot is equipped with a modified, low-cost ultrasonic transducer. This transducer can function either as a receiver or as an emitter. For localization to be effective, it is important that the sensor can detect signals coming from any direction around the Millibot. As is illustrated in Figure 4, an ultrasonic transducer is positioned to faces straight up and all incoming and outgoing sound waves are reflected by an aluminum cone. The result is a 360 degree coverage in the horizontal plane. The ultrasonic transducer with reflector is about 2.5cm tall. It can measure distances up to 3m with a resolution of 8mm while consuming only 25mW. The construction and design of this detector was paramount in achieving a beaconing system at this scale.

An important advantage of the Millibot localization system is that it does not rely on fixed beacons. Instead, a minimum of three Millibots (but not necessarily always the same three) serve as beacons at any time. The Millibots that serve as beacons

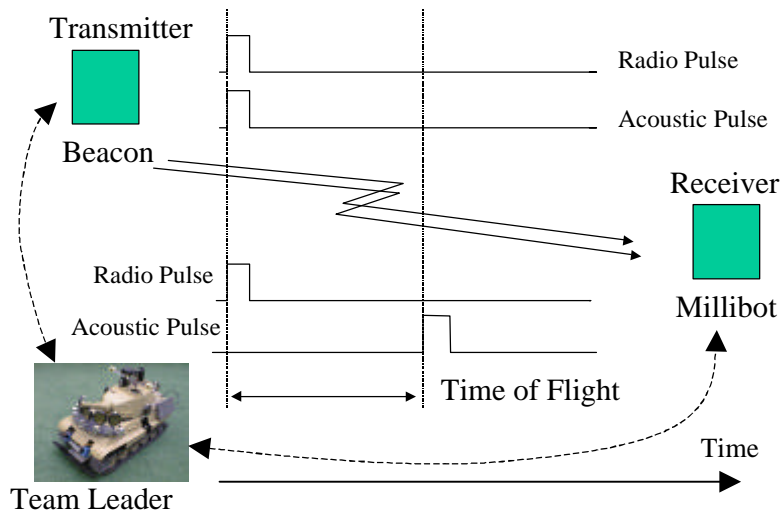
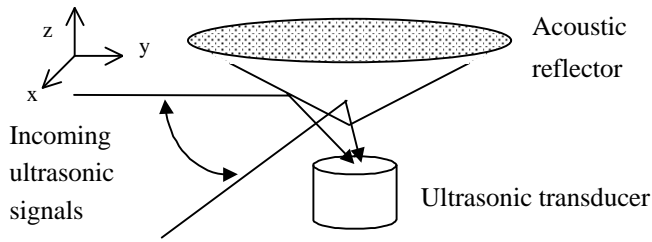


Figure 3: Ultrasonic distance measurement.



**Figure 4 : The acoustic reflector**

remain stationary. The other robots can move around in the area that is within reach of the beacons. While they sense the environment, they can determine their position with respect to the current beacons. When the team has explored the area covered by the current beacons, other robots will become stationary and start serving as beacons. In this fashion, the team can move over large areas while maintaining good position estimates.

The localization algorithm is most accurate when the beacons are at the vertices of an equilateral triangle. When a team moves over a large distance, the beacon that is farthest removed from the goal will be replaced by a Millibot in a position closer to the goal and equidistant to the other two beacons. This leap-frogging approach allows a team to move forward, while always maintaining three stationary beacons in known locations.

For example, in a team of four robots, three robots establish the initial geometric formation. The fourth robot drives to the center of the formation and determines the angle to the group goal. Based on that angle it selects a path between two of the three robots that takes it closest to the goal. The robot continues on this path until it forms a new triangle with those same two robots. If no other robots are available, the robot farthest away breaks ranks and performs the same actions. The group slowly moves towards the goal while maintaining localization. When limited to four robots, only one robot is moving at any one time and the others are fixed to maintain a relative marker. However, robots not participating in the beacon formations are free to wander in and out of the formation to perform their sensing tasks. If more than four robots are available for operating as beacon sources, the formation can grow beyond two triangles at any one time to produce a formation highway. The advantage to building a highway is that robots free of the formation can move quickly back and forth along the triangle highway without having to wait for the formation to move.

#### 4. MAPPING AND EXPLORATION

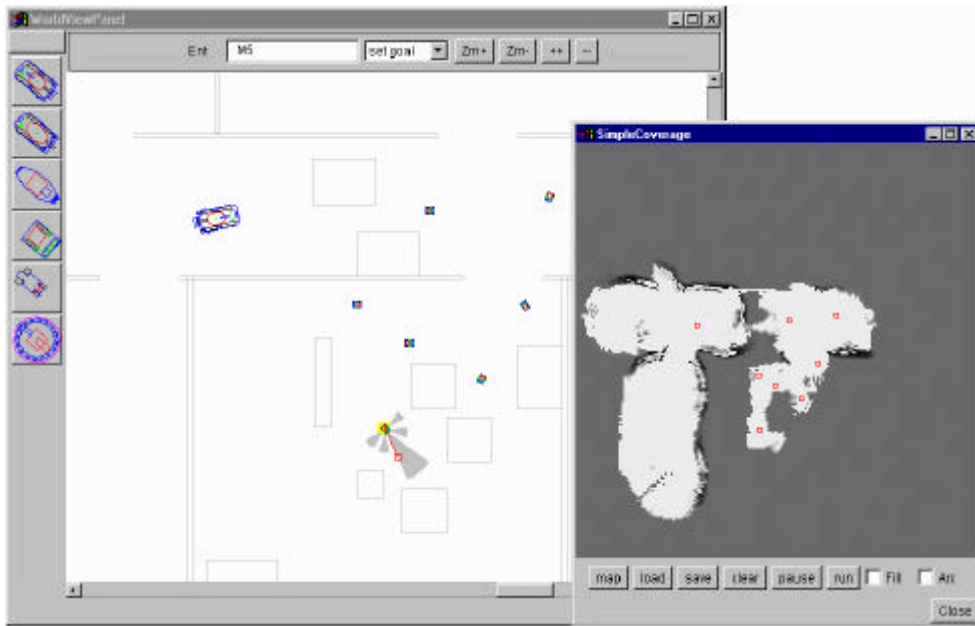
The ability for a single robot to map any significant area is difficult, especially for robots at this scale. Even with its long-range sonars, the Millibot is limited to a detection range of only about 2 meters in a relatively tight cone. However, a group of Millibots can be equipped with similar sensors to cover more area than a single robot and in less time. During operation, each robot collects information locally about its surroundings. This data is transmitted to the team leader where it is used to build a local map centric to that robot. The team leader can utilize local map information to direct the Millibot around obstacles, investigate anomalies or generate new paths. The team leader can also merge the information from several local maps into a single global map to provide a complete view of the environment to the user.

We are using an occupancy grid method with a Bayesian update rule to combine sensor readings from different robots and from different time instances<sup>25,26,27</sup>. In an occupancy grid, the environment is divided into homogeneous cells. For each cell, a probability of occupancy is stored. An occupancy value of zero corresponds to a free cell, a value of one corresponds to a cell occupied by an obstacle. Initially, nothing is known about the environment and all the cells are assigned a value of 0.5 (equally likely to be occupied or free).

The mapping algorithm uses a Bayesian update rule<sup>25</sup>:

$$\text{Occup}(c | S^{(1)}, \dots, S^{(T)}) = 1 - \left( 1 + \frac{\text{Occup}(c | S^{(T)})}{1 - \text{Occup}(c | S^{(T)})} \frac{\text{Occup}(c | S^{(1)}, \dots, S^{(T-1)})}{1 - \text{Occup}(c | S^{(1)}, \dots, S^{(T-1)})} \right)^{-1} \quad (1)$$

Equation (7) updates the occupancy probability for cell  $c$ ,  $\text{Occup}(c | S^{(1)}, \dots, S^{(T)})$ , based on the current sensor reading,  $\text{Occup}(c | S^{(T)})$ , and the *a priori* probability,  $\text{Occup}(c | S^{(1)}, \dots, S^{(T-1)})$ . Any sensor that can convert its data into a probability



**Figure 7 : Collaborative Mapping**

that a particular cell is occupied can be merged into the same map. This means that data generated by a short-range proximity detector can be merged with data from a sonar range module or even a camera.

Figure 5 represents an occupancy grid generated from a group of Millibots and a single team leader mapping a small room. For this experiment, each Millibot was equipped with a five-element proximity detector and a single sonar ranging module. The maps of each robot were merged to generate a complete map of the room.

## 5. EXAMPLE SCENARIO

To provide a conceptual view of the capabilities of a team of robots, we composed a scenario that was designed to exploit the features of a group of Millibots and emphasize the heterogeneous nature of the team.

Imagine a scenario in which a team, consisting of seven Millibots and a single tank robot, is deployed to investigate an office building or lab for which only a rudimentary floor plan is provided. It is known that there will be spaces unreachable by the larger tank robot. Therefore, a team that includes Millibots is deployed to explore the given space and detect any objects or persons not found in the plans.

To accomplish the mission, a team of Millibots is constructed with various sensor modules. Many modules will be common to each Millibot while others will be specific to Millibots performing a specialized task. To provide mapping ability for the spaces covered by the Millibots, each Millibot is equipped with either a short range or long range sonar range module. Since the space will mostly be open hallways and offices, most of the robots will carry the long-range sonar modules. However a few will be equipped with short range sensors to provide information from tightly spaced obstacles or corridors. Along with sonars, each robot will also carry an infrared proximity module to provide low level obstacle avoidance. The proximity module is necessary because the sonar use is limited due to interference with the localization system and cannot provide continuous protection.

Some robots are equipped with specialized modules. For example, one robot is equipped with a second communication module that allows the robot to act as a repeater. When this robot detects a message on one channel, it repeats it on the other. The ability to repeat messages allows the Millibot group to maintain communications with its team leader even if it the group moves out of range. Additionally, one Millibot is designated to carry a camera module. This module provides the group with the ability to identify and classify detected obstacles. However, because of the power requirements of the camera module, the camera will remain powered off until it is needed by the group for identification.



The specific mobility platform is task dependent also. Since the Millibots will be travelling on a tiled floor, they are equipped with a track driven mobility platform equipped with rubber treads. To complete the robot, a main processor and communication link are attached. Finally, a localization module is added to each robot to provide position estimation.

Figure 5 shows an example of the progression of the team of robots in this scenario. The tank robot has stopped on the left of a set of obstacles blocking its progress. The team of Millibots has moved between the obstacles and fanned out to surround and map the blocking obstacles. The camera robot was positioned and a video image was used to identify the obstacles. The group continued to move and has begun exploration into a room containing more obstacles. Several robots have positioned themselves to provide localization coverage while the remaining robots are moving in and out of the coverage to build a map of the area. When the low-level map has provided enough detail, the camera robot will again be called to provide a video image for classification. The robot with the second set of radio modules has been positioned to provide communications between the group in the room and the tank robot down the hall.

## 6. SUMMARY

In this paper we have presented the design of a distributed robotic system consisting of very small mobile robots called Millibots. Although the Millibots are small they still contain a full set of integrated capabilities including sensing, computation, communication, localization and mobility. To expand the capabilities even further, the Millibots have been designed in a modular fashion allowing one to easily create specialized robots with particular sensing configurations. By combining several such specialized robots one can create a team with a very broad range of capabilities while still maintaining a small form factor.

An important subsystem of the Millibots is a novel ultrasound-based localization system. This system has the important advantage over currently existing systems that it does not require any fixed beacons. By using the Millibots alternately as beacons and as localization receivers, the team as a whole can move in a leap-frog fashion while maintaining accurate localization estimates at all times.

Tracking robot positions accurately is especially important for the mapping and exploration application that we have implemented. Each robot explores an unknown environment with its sonar and IR sensors. A team leader collects all the sensor information and integrates it into a global view of the environment. The team leader uses an occupancy grid representation with a Bayesian update to fuse the sensor data over time.

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