Centibots: Very Large Scale Distributed Robotic Teams

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Problem and Related Work

In this paper, we describe the development of Centibots, a framework for very large teams of robots that are able to perceive, explore, plan and collaborate in unknown environments. Teams consist of approximately 100 robots which can be deployed in unexplored areas and which can efficiently distribute tasks among themselves; the system also makes use of a mixed initiative mode of interaction in which a user can easily influence missions as necessary. In contrast to simulation-based systems which abstract away aspects of the environment for examining component technologies, our design reflects an integrated, end-to-end system.

The experiments described here involve the coordinated deployment of ≈ 100 robots in three successive stages: (1) a mapping stage involving the coordinated exploration of the environment while simultaneously constructing a very high accuracy occupancy map using laser range finders; (2) a search stage in which the environment is exhaustively searched for a predefined object of interest (OOI); and (3) an intruder detection stage in which robots are distributed throughout the environment to ”guard” the OOI by continuously sensing the environment for human intruders. This stage included recharging a portion of the robots to prove the system could continue indefinitely. Previous work has largely focused on isolated aspects of our system, including multi-robot exploration (Burgard *et al.* 2000), architecture(Gerkey & Matarić 2003), task allocation(Nair, Tambe, & Marsella 2003), coordination(Modi *et al.* 2003), and human interaction(Tews, Mataric, & Sukhatme 2003). In addition to integrating all these aspects into a working system, we had to make advances in various technical and system engineering areas, as described in the next section.

Technical Approach

Mapping and exploration We developed novel decision-theoretic algorithms for robot teams to effectively coordinate mapping. Key challenges are that the robots can start from multiple, unknown locations; communication is not guaranteed; and there is no central coordination of the mapping process. We have used a multi-robot version of Lu-Milios mapping, together with novel Bayesian learning algorithms, to solve this difficult problem (Lu & Milios 1997). If not in communication, each robot is able to explore on its own. Otherwise, the robots coordinate their exploration strategies, estimate and actively verify their relative locations (if unknown), and merge their sensor data into a globally consistent map (Ko *et al.* 2003) (also see figures 1, 2).

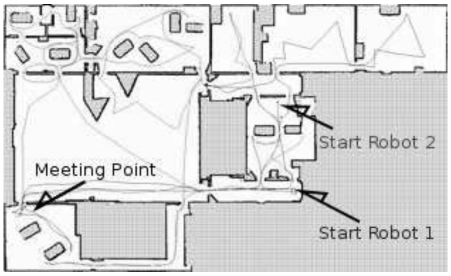

Figure 1: Map and paths during exploration. The robots start exploring from different, unknown locations. After finding a good hypothesis for their relative locations, they meet at the meeting point, merge their maps, and continue coordinated exploration under limited communication.

Spatial reasoning We extended current methods of spatial reasoning to associate spatial regions with team goals. A topological graph is abstracted from a Voronoi diagram and labelled with metadata to enable reasoning about movement, placement and coordination of robots. See figure 3.

Robot teams We developed an adaptive team organization for scalable distributed control based on the dispatcher metaphor. Robots can take on tasks as needed, request help for a task, and cause new tasks to be created. The dispatcher can run on any system in the network to facilitate the necessary coordination.

Wireless communication For effective information flow under a constantly changing network topology, we developed a short range communications system and used the existing Jini(Waldo 1999) system over a dynamically reconfiguring multihop, ad-hoc network(Ogier *et al.* 2002). In addition, the mixed initiative interface and the spatial reasoning could be used to create a network backbone when necessary.

Mixed-initiative interface We developed new mixed initiative methods for single users to track and influence missions involving hundreds of robots. The robots can be con-

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Figure 2: Generated map (free space in light gray) overlayed with a CAD model (in dark gray) of the building. The CAD model was generated from manual measurements by a third party. Map edges overlap in black.

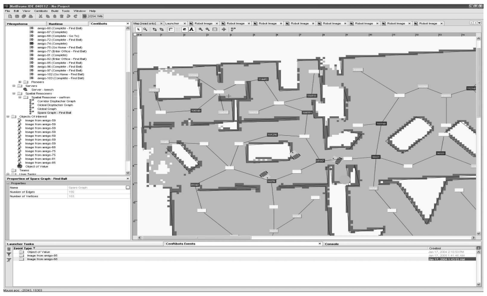

Figure 3: Mixed initiative interface with the graph structure extracted from the occupancy map. Robots are assigned to graph nodes based on the expected utility for the overall task.

trolled from the level of individual motion commands to task based behavior as part of a group. Robot groups may be constructed and reconstructed dynamically. When needed, groups can be manually reassigned tasks.

Experiments

The Centibots project is unique in having an experimental validation conducted by an outside group. For a week in January 2004, the Centibots were tested at a $700m^2$ building in Ft. A.P. Hill, Virginia. We had no access to one third of the environment until the beginning of the experiments. The system was tested under controlled conditions, with a single operator in charge of the robot team via our mixed initiative interface. The evaluation criteria varied by stage. For mapping, these included time to create a map, topological accuracy, and percent of area mapped. For searching, the criteria were time to locate OOI(s), positional accuracy, topological accuracy, and false detections. For the protection stage, the criteria were detection, and time to first detection.

There were four 'standard' runs, going through the three stages: mapping, searching and guarding. For single robot mapping, two runs with single mappers yielded 22 and 26 minutes running time, with 100% topological accuracy for both, and 97 and 98% area accuracy. For two robots mapping, two runs yielded 17 and 19 minutes, 100% topological accuracy, with 96% area accuracy. For searching, the OOI was found in the first three runs with 100% topological accuracy with mean error in position of the OOI of 14cm. The times to find the OOI were 34, 71 and 16 minutes. The OOI was not found in the fourth run after 53 minutes of searching. One and two false positive occurred in tests two and four, respectively. For guarding, each run consisted of four separate intrusions. The detection percentages for the four runs were: 75, 50, 25[1], 100%. The average times to first detection for each run were 8, 8, 8 and 48 seconds. There was one false positive in the first run. The number of robots used for the last two stages were: 66, 55, 43 and 42.

Experiments were also performed on isolated stages of the system. For mapping, three robots were used, with the same start location. This resulted in a 1.41 times improvement in the time to map compared to the average standard run. For two mappers with different start positions, the time to map worsened by a factor of 0.82. The accuracy for both cases was the same as in the standard run, up to 1%.

For searching, five OOIs were placed. All five were detected after approximately one hour, but communications failures led to two of these detections not being reported to the command center in a reasonable fashion. Also, a rapid launch experiment was devised to determine the speed at which robots could be deployed. For this, 37 robots were deployed in 555 seconds (one robot/15 seconds).

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[1] A misconfigured track filter was at work for this result, and was fixed before the next run