ARIEL: Autonomous Robot for Integrated Exploration and Localization

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Introduction

In order for a robot to add its perceptions to a map, it needs to know its location, but in order for a robot to determine its location, it often needs a map. This is a central dilemma in robot exploration. Robots often use dead reckoning to estimate their position without a map, but wheels slip and internal linkages may be imprecise. These errors accumulate over time, and the robot's position estimate becomes increasingly inaccurate.

We have addressed this problem in ARIEL. ARIEL uses frontier-based exploration (Yamauchi 1997) to navigate to unexplored space and to map the territory that it perceives, and continuous localization (Schultz, Adams, and Grefenstette 1996) to maintain an accurate estimate of its position at all times.

ARIEL has been implemented on a Nomad 200 mobile robot equipped with sonar, infrared, and laser range sensors. ARIEL runs on a SPARCstation 20 and communicates with the robot's onboard Pentium processor via radio ethernet. This system has been used to explore real-world office environments. We will demonstrate ARIEL at the AAAI-97 Robot Exhibition.

We are also interested in using genetic algorithms to automatically learn behaviors for controlling mobile robots, and we will be demonstrating some of those learned behaviors at the Exhibition.

Frontier-Based Exploration

Most mobile robot applications require the ability to navigate. While many robots can navigate using maps, and some can map what they can see, few can explore. Usually, a human must map the territory in advance, providing either the exact locations of obstacles (for metric maps) or a graph representing the connectivity between open regions (for topological maps). As a result, most navigating robots become useless when placed in unknown environments.

Our goal is to develop exploration strategies for the complex environments typically found in real office buildings. Our approach is based on the detection of *frontiers*, regions on the border between open space and unexplored space. From any frontier, the robot can see into unknown territory and add its new observations to the map.

We use evidence grids (Moravec and Elfes 1985) as our spatial representation. To detect frontiers, occupancy probabilities are thresholded, and each cell is placed into one of three classes: open, occupied, or unknown. A process analogous to edge detection and region extraction in computer vision is used to find the boundaries between open space and unknown space. Any open cell adjacent to an unknown cell is labeled a frontier edge cell. Adjacent edge cells are grouped into frontier regions, and any frontier region above a certain minimum size is considered a frontier.

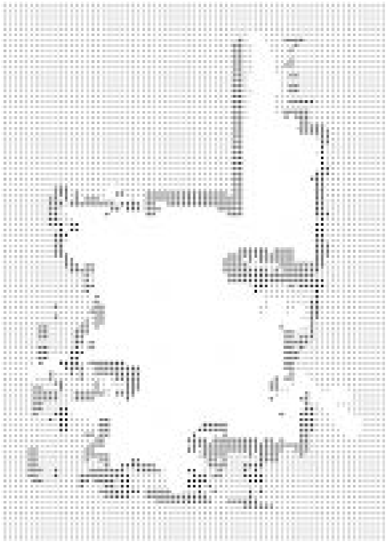

Figure 1: Evidence grid from frontier-based exploration

Initially, ARIEL sweeps its sensors to generate a new evidence grid. Then it detects frontiers within this grid and attempts to navigate to the closest frontier. When ARIEL arrives at the frontier, or if it is blocked from reaching the

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frontier, it sweeps its sensors again, and adds the new information to its map. Then, it detects frontiers in the extended map and attempts to navigate to the closest unvisited frontier. This process is repeated until all frontiers are visited or determined to be inaccessible.

In this way, ARIEL is able to start with no information about its environment and then use frontier-based exploration to map all accessible regions. After exploration, ARIEL uses this map to navigate throughout the environment. Figure 1 shows the evidence grid map constructed by ARIEL as it explored a cluttered office, after entering from an adjacent hallway.

Continuous Localization

Without some way to correct for accumulated odometry error, the maps constructed during exploration would become increasingly inaccurate. ARIEL uses continuous localization to compensate for odometry error and maintain an accurate position estimate at all times.

Previous techniques for localization have looked at learning and recognizing landmarks in the environment, either as geometric representations or as a representation of sensor readings. Our localization technique does not need to rely on the presence of landmarks, but instead uses the entire local environment of the robot to determine its location.

An important issue in localization is how often to relocalize the robot in its environment. Many existing techniques only relocalize when either an error in position is detected or after an unacceptable level has accumulated. In our method, ARIEL continuously relocalizes by making regular small corrections instead of occasional large corrections. The benefit is that the error is known to be small, and fast correction techniques can be used.

Frontier-based exploration extends the global evidence grid map whenever ARIEL moves to a new frontier. In addition, continuous localization builds short-term perception maps of its local environment. These maps are of a short duration, and typically contain only very small amounts of positional or rotational error. These short term maps are then used to position the robot within the global map via a registration process, the offset of which is used to correct the robot's current odometry.

In this previous research with a fixed map (Schultz, Adams, and Grefenstette 1996), we have shown that continuous localization is capable of eliminating accumulated odometry errors with a resulting constant translational error on the order of five inches, or approximately the size of an evidence grid cell. Preliminary experiments with ARIEL have demonstrated similar levels of accuracy. Current research aims to allow the system to adapt to changing environments by updating the global map using information from more recent short-term maps (Graves, Schultz, and Adams 1997).

Speech and Gesture Recognition

In order for humans to interact with ARIEL, we have added an interface that allows people to give the robot commands using speech and hand gestures. For example: a person can gesture toward a location in the room and say, “Go over there.” This system uses an off-the-shelf speech recognition device along with NAUTILUS, a natural language processing system developed in-house (Wauchope et al. 1997). The robot's laser rangefinder is used to sense hand gestures.

Learned Behaviors

In other research, we have also used genetic algorithms to evolve complex behaviors for multiple mobile robots (Schultz, Grefenstette, and Adams 1996). The task involved one robot shepherding another. These behaviors were evolved in simulation, then transferred and validated on the real mobile robot. In addition to ARIEL, we will also demonstrate a number of learned behaviors at the Exhibition, including obstacle avoidance and reactive navigation.

Acknowledgments

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