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Sharing Information Efficiently in Cooperative Multi-Robot Systems

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INTRODUCTION

Multi-robot systems (MRS) are sets of intelligent and autonomous mobile robots that are assumed to cooperate in order to carry out collective missions (Arai, Pagello, & Parker, 2002; Cao, Fukunaga, & Kahng, 1997; Rocha, Dias, & Carvalho, 2005). Due to the expendability of individual robots, MRS may substitute humans in risky scenarios (Maimone et al., 1998; Mataric & Sukhatme, 2001; Parker, 1998; Thrun et al. 2003). In other scenarios, they may relieve people from collective tasks that are intrinsically monotonous and repetitive. MRS are the solution to automate missions that are either inherently distributed in time, space, or functionality.

MRS involve the distribution of sensors, computation power and mission-relevant information. This inherent distribution is both an opportunity and a challenge. On one hand, it endows MRS with interesting features, such as space and time distribution, managing complexity through distribution, distribution of risk and increased robustness (Arkin & Balch, 1998). On the other hand, these potential advantages and their utility are to a greater extent dependent on the effective cooperation among robots when performing some collective mission (Rocha, 2005).

Since information is intrinsically distributed, cooperation requires, in turn, efficiently sharing information through communication (Rocha et al., 2005). A method for efficiently sharing information within a MRS is herein presented, which is based on an information utility criterion (Rocha et al., 2005). This concept is illustrated on MRS whose mission is to build cooperatively volumetric maps.

Robotic Mapping

Robotic mapping addresses the problem of acquiring spatial models of physical environments with mobile robots equipped with distance sensors, such as cameras, range finders and sonars. Usually the map is not the goal itself and those mobile robots are used to safely navigate within the environment and perform other useful tasks that require an up-to-date map of the environment (e.g., search and rescue). But mobile robots may also be used for building detailed maps of indoor environments (Martin & Moravec, 1996; Stachniss & Burgard, 2003), being particularly useful on mapping missions of hazardous environments for human beings, such as underground mines (Thrun et al., 2003) or nuclear facilities (Maimone et al., 1998).

As sensors have always limited range, are subject to occlusions and yield noisy measurements, mobile robots have to navigate through the environment and build the map iteratively. Some key challenges in this context are the sensor modeling problem, the representation problem, the registration problem and the exploration problem (Thrun, 2002). This article focuses on efficiently sharing sensory information within a team of mobile robots, so as to build a volumetric map in less time than a single robot.

Sharing Information within Multi-Robot Systems

Most of the work about multi-robot systems (MRS) has been devoted to the definition of different architectures (Gerkey & Mataric, 2002; Mataric et al., 2001; Parker, 1998) that rule the interaction between the behaviors of individual robots. Communication is a central issue of MRS because it determines the possible modes of interaction among robots, as well as the ability of robots to build successfully a world model, which serves as a basis to reason and act coherently towards a global system goal. Communication may appear in three different forms of interaction (Cao et al., 1997): (1) *via environment*, using the environment itself as the communication medium (stigmergy); (2) *via sensing*, when an agent knowingly uses its sensing capabilities to observe and perceive the other robots' actions; and (3) *via communication*, using a communication channel to explicitly exchange messages among robots, thus compensating perception limitations.

This article presents a distributed group architecture which endows robots with a cooperation scheme whereby explicit communication is efficiently used to increase the robot's individual awareness based on a criterion of information utility (Rocha et al., 2005).

PROBABILISTIC VOLUMETRIC MAPS

This section outlines a grid-based probabilistic framework for representing and updating volumetric maps. Further details can be found in Rocha et al. (2005).

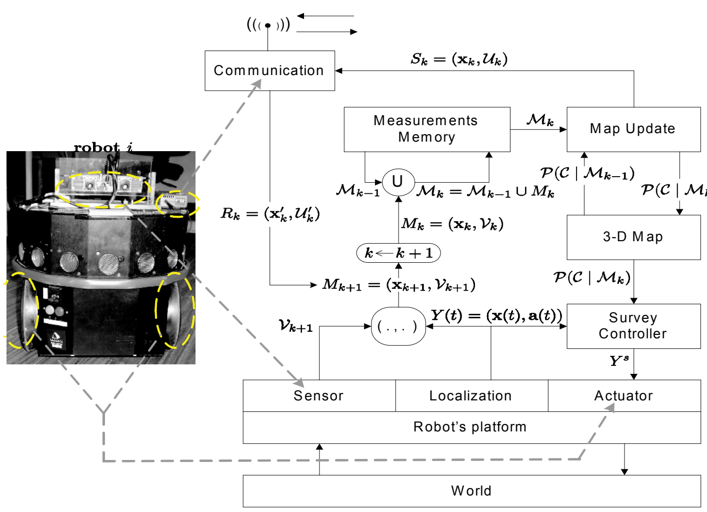
Architecture Model

The functional blocks of a mobile robot carrying out a volumetric mapping mission (Rocha et al., 2005) is depicted in Figure 1. The mobile robot's platform is assumed to have a sensor, a localization module and an actuator. The sensor provides new sets of vectors V_{k+1} where obstacles are detected from the current sensor's pose $Y(t)$=($\mathbf{x}(t)$,$\mathbf{a}(t)$). The localization module gives the sensor's pose $Y(t)$, including position $\mathbf{x}(t) \in R^3$ and attitude $\mathbf{a}(t)$. The actuator changes the sensor's pose (robot's pose) accordingly with a new selected exploration viewpoint Y^S. New data from the robot's sensor is associated with its current pose, given by the localization module, to form a new batch of measurements $M_{k+1} = (\mathbf{x}_{k+1}, V_{k+1})$. Then, index k is incremented and the new batch of measurements becomes the current batch M_k. The memory of measurements is updated as $M_k = M_{k-1} \cup$. The previous map $P(C \mid M_{k-1})$ is updated upon the new batch of measurements M_k, which yields the current map $P(C \mid M_k)$. The current map is used to choose a new target pose Y^S which is the reference input to the robot's actuator.

Volumetric Model

Rocha et al. (2005) proposed a grid-based model to represent volumetric maps with an explicit representation of uncertainty through the entropy concept. It is based on coverage maps (Stachniss et al., 2003), which are grid-based probabilistic maps (Moravec et al., 1985) wherein the occupancy of a cell is modeled through a continuous random variable—the cell's coverage. The volumetric model assumes that a 3-D discrete grid Y is defined, which divides the robotic team workspace into equally sized voxels (cubes) with edge $\varepsilon \in R$ and volume ε^3 (Figure 2). The portion of the volume of

Figure 1. Block diagram showing the relation between different parts of the process and the resources of a given mobile robot the fleet



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