Encyclopedia of E-Collaboration

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Information Science REFERENCE
INFORMATION SCIENCE REFERENCE
Hershey · New York

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Cover Design: Lisa Tosheff
Printed at: Yurchak Printing Inc.

Published in the United States of America by
Information Science Reference (an imprint of IGI Global)
701 E. Chocolate Avenue, Suite 200
Hershey PA 17033
Tel: 717-533-8845
Fax: 717-533-8661
E-mail: cust@igi-global.com
Web site: http://www.igi-global.com/reference

and in the United Kingdom by
Information Science Reference (an imprint of IGI Global)
3 Henrietta Street
Covent Garden
London WC2E 8LU
Tel: 44 20 7240 0856
Fax: 44 20 7379 0609
Web site: http://www.eurospanonline.com

Library of Congress Cataloging-in-Publication Data

Encyclopedia of e-collaboration / Ned Kock, editor.
p. cm.
Summary: "This encyclopedia provides the most comprehensive compilation of information on the design and implementation of e-collaboration technologies, their behavioral impact on individuals and groups, and theoretical considerations on links between the use of e-collaboration technology and behavioral patterns. It delivers indispensable content to libraries and researchers looking to develop programs of investigation into the use of e-collaboration"--Provided by publisher.
Includes bibliographical references and index.
ISBN 978-1-59904-000-4 (hardcover) -- ISBN 978-1-59904-001-1 (ebook)
1. Project management. 2. Virtual work teams. 3. Human-computer interaction. 4. Information technology. I. Kock, Ned F., 1964-
HD69.P75.E53 2007
658.4'0220285--dc22
2007022233

British Cataloguing in Publication Data
A Cataloguing in Publication record for this book is available from the British Library.

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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 | M_{k-1}) is updated upon the new batch of measurements M_k, which yields the current map P(C | 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

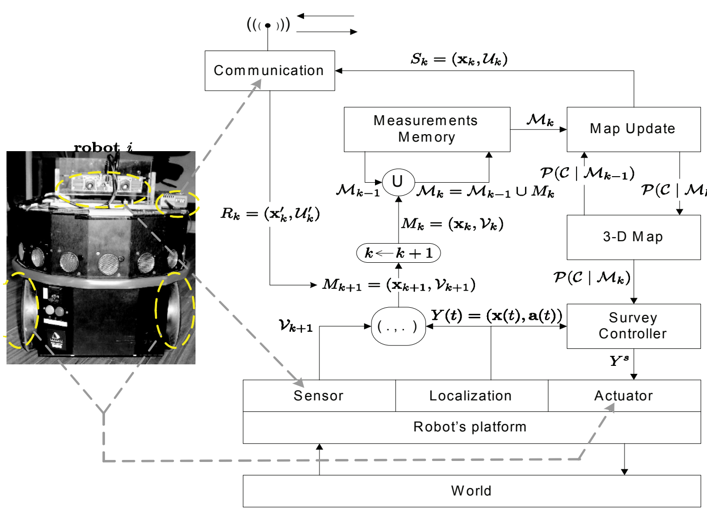
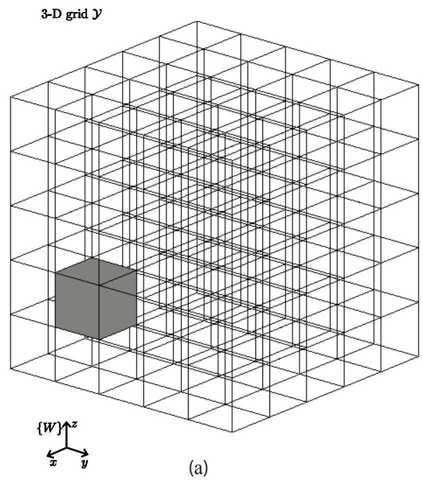
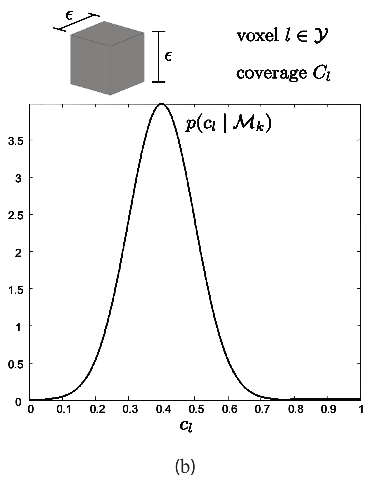


Figure 2. Volumetric discrete grid: (a) the grid divides the workspace into equally sized voxels; (b) the coverage C_l of each voxel $l \in Y$ with edge ε, given the sequence M_k of k batches of measurements, is modeled through a probability density function $p(c_l \mid M_k)$.





voxel $l \in Y$ which is covered (occupied) by obstacles is modeled through the continuous random variable C_l taking values c_l in the interval $0 \leq c_l \leq 1$, and having $p(c_l)$ as its probability density function (pdf). The objective when building a map is to obtain for each voxel $l \in Y$ an estimate as accurate as possible about its coverage C_l.

The map's entropy is used to define the mission execution time. After defining a given map's entropy threshold H_{th}; that is, the minimum map's quality that robots must accomplish at the end of the mapping mission, the mission execution time $t_{k_{max}}$ is such that:

$$H(t_{kmax}) \leq H_{th} \wedge \forall_k < k_{max},\ k \in N_o,\ H(t_k) > H_{th}. \qquad (4)$$

It is associated with the k_{max}-th batch of measurements; that is, the last batch of measurements acquired by the robot with the lowest entropy at the end of the mission.

Figure 4 shows several versions of a map along a mapping mission with two robots.

EFFICIENTLY SHARING INFORMATION

In the absence of a centralized controller, multi-robot systems involve the distribution of control and sensory data gathered from sensors. Therefore, in order to attain a coherent and useful team behavior, a distributed control scheme is required so as to barter efficiently resources and, as well, information (Rocha, 2005). The main advantage of distributing control and data is to easily scale up the robotic systems to an arbitrary number of robots, while maintaining the system's reliability and robustness.

Since information is distributed, efficiently sharing information among robots is crucial. Although there are other forms of conveying information, distributed control relies to a greater extent on explicit communication. Rather than addressing the *communication structure* in multi-robot systems (Balch & Arkin, 1994; Stone & Veloso, 1999; Gerkey et al., 2002; Ulam et al., 2004), it is worth considering the *communication content;* that is, "What is useful (task-relevant) to be communicated?" The question requires in turn assessing information utility (Rocha et al., 2005). The goal behind these questions is to avoid communicating redundant information so as to use efficiently communication.

Information Utility

Whenever a robot gets a new batch of measurements M_k, the associated information utility can be measured in terms of a decrease of the map's entropy $H(C)$. The map's entropy is a measure of the map's uncertainty and its decrease within a period of time is a measure of the information utility of the measurements gathered within the same period of time, in terms of their utility on improving the map's accuracy (Rocha et al., 2005).

Sharing Useful Sensory Information

Although the block diagram depicted in Figure 1 refers to a single robot, it is sufficiently general to represent a multi-robot system. The interaction of a robot with other robots is represented through the communication block and its associated data flow.

Whenever a robot gets a batch of measurements $M_k = (\mathbf{x}_k, V_k)$, it sends to its teammates a subset of measurements $S_k = (\mathbf{x}_k, U_k)$ through the communication module, containing the most useful data $U_k \subseteq V_k$ which has just been acquired from its sensor. This module can also provide the robot with batches of measurements $R_k = (\mathbf{x}'_k, U'_k)$ given by other robots and the map is updated accordingly. Cooperation among robots arise because of this reciprocal interaction (Rocha et al., 2005).

The set:

$$\mathcal{U}_k = \{\overrightarrow{\mathbf{u}}_{k,1}, \ldots, \overrightarrow{\mathbf{u}}_{k,s_k}\} \subseteq \mathcal{V}_k \quad (7)$$

contains s_k measurements selected to be communicated. The sensor's position $\mathbf{x}_k$ from where those measurements were gathered is also sent, since it is required for registering those measurements in the local map of other robots.

Whenever a robot receives a batch of u_k communicated measurements $R_k = (\mathbf{x}'_k, U'_k)$, it updates its local map as if measurements U'_k would have been gathered by its own sensor when located at position $\mathbf{x}'_k$.

As communication channels have always limited capacity, a robot acting as information provider should limit the amount of communicated data, *i.e.* select the most useful measurements gathered from its own sensors. Equation (5) provides a way to do this: each robot computes this equation in order to assess the information utility of measurements $\vec{\mathbf{v}}_{k,i} \in V_k$ and classify them by utility.

Let define s_{kmax} as being the maximum number of allowable communicated measurements at a given time instant. Let also define I_{min} as being the minimum allowable information utility for a communicated measurement.

The set (7) is built in such a way that the proposition:

$$\begin{aligned}&(s_k \leq s_{k_{max}} \wedge \\ &s_k < s_{k_{max}} \Rightarrow \forall_{\overrightarrow{\mathbf{v}}_{k,z} \in \mathcal{V}_k \backslash \mathcal{U}_k},\ I_{k,z} < I_{min} \wedge \\ &\forall_{\overrightarrow{\mathbf{u}}_{k,j} \in \mathcal{U}_k},\ I_{k,j} \geq I_{min} \wedge \forall_{\overrightarrow{\mathbf{v}}_{k,w} \in \mathcal{V}_k \backslash \mathcal{U}_k},\ I_{k,w} \leq I_{k,j})\end{aligned} \quad (8)$$

is true. It is true if the batch size is less than the maximum size and it includes the most useful measurements.

RESULTS AND DISCUSSION

The architecture model shown in Figure 1 was implemented in the mobile robots depicted in Figure 3, which use stereo-vision as range sensor. They were used to carry out experiments aiming at studying the influence of the information sharing parameters I_{min} and s_{kmax} on the team's performance, through the comparison of the mission execution time t_{kmax} with different values for those parameters (Rocha et al., 2005). The robots started each experiment with a maximum entropy map and followed the exploration method proposed by Rocha et al. (2005), which is based on the uphill gradient of the map's entropy, in order to explore the environment until the entropy threshold $H_{th} = 500$ was attained.

Table 1 summarizes the obtained results with the team of two robots, which are however extensible and can be generalized to teams having an arbitrary number of robots because the robots' program is intrinsically scalable to any team size. The fourth column shows the ratio between the mission execution time $t_{kmax}(2)$ with two robots and $t_{kmax}(1)$ with one robot. Given that voxels' coverage beliefs were always Gaussians, the values used for I_{min}, {0, 0.00723, 0.01450, 0.07400, 0.15200, 0.32193}, meant an average reduction on the standard deviation of the influenced voxels by a measurement of at least {0%, 0.5%, 1%, 5%, 10%, 20%}, respectively. The fifth column shows the total number of measurements m_T gathered by a robot along the mission, which is given by equation (9).

$$m_T = \sum_{k=1}^{k_{max}} m_k. \quad (9)$$

The sixth column shows the total number of received measurements from the other robot u_T, which is computed through equation 10.

$$u_T = \sum_{k=1}^{k_{max}} u_k. \tag{10}$$

In each experiment (row of the table), the results refer to the robot that first attained the entropy threshold H_{th}; that is, the robot having the best map at the end of the mission. Figure 4 presents an example of the maps obtained by the two robots along a 3-D mapping mission. As it can be observed, robot 2 held the best map for the instant times represented in the figure, which means that robot 2 reached H_{th} first. The time $t_k(1)$ that a single robot would need to obtain the represented maps is also shown, so as to better understand the reduction of the mission execution time yielded by a team of cooperative mobile robots.

Advantages Provided by Cooperation

The graph on the left of Figure 5 compares the map's entropy H(t) for the single robot case and for the fastest experiment with two robots (fourth row of Table 1). It shows a non-linear increase of the mission execution time with a decrease of the map's entropy. It also shows that robots' cooperation accelerated the reduction of the map's entropy and led to a reduction of 28% in t_{kmax}. As robots shared useful measurements through communication, each robot was able to integrate in its map a greater number of measurements per time unit and achieved a faster reduction of its map's entropy. The graph on the right of Figure 5 shows that although the two values of m_T were similar, measurements were obtained within time intervals t_{kmax} quite different.

FUTURE TRENDS

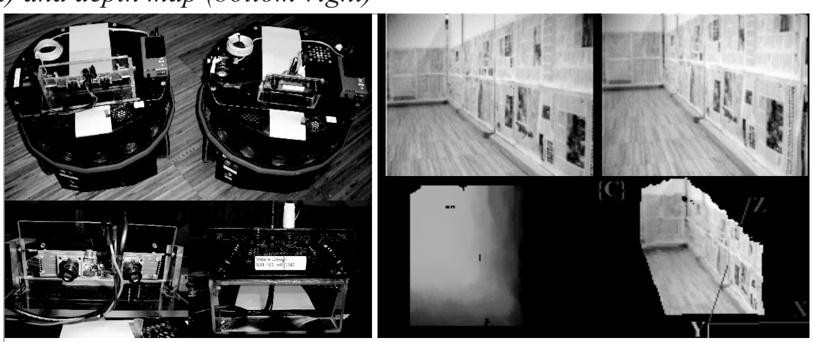
Building a volumetric map is essentially an exploration mission. The goal is to completely sense the environment so as to accumulate sufficient sensory evidence and build a consistent spatial model with low uncertainty; that is, a map with low entropy. The previous section showed a performance gain which is far away from a linear improvement with team size. This is mainly due to the lack of coordination of the robots' exploration actions and thus it is worth addressing this problem in the future.

Another important future direction is to demonstrate the application of the information sharing method herein presented to other robotics application domains than robotic mapping and, as well, to domains outside robotics. The essential problem—efficiently sharing information—is indeed relevant to other domains than robotics. For instance, human organizations and human societies involve complex cooperative interactions supported on some flow of information. Redundancy, consistency, and information utility are also crucial issues to these complex societal systems.

CONCLUSION

This article addressed the problem of efficiently sharing information within multi-robot systems in the context of robotic mapping. After briefly presenting a probabilistic framework which allows representing and updating a volumetric map upon range measurements, information utility was formulated through mutual information, an

Figure 3. Mobile robots used in the mapping experiments: (a) Scout mobile robots (top) equipped with stereo-vision sensors (bottom); (b) a stereo image pair (top) and its associated disparity (bottom-left) and depth map (bottom-right)



(a) (b)

Table 1. Results obtained within experiments with two robots and different parameters ruling the information sharing

$s_{k_{max}}$	I_{min}	$t_{k_{max}}$	$\frac{t_{k_{max}}(2)}{t_{k_{max}}(1)}$	m_T	u_T	
500	0.01450	8483	0.94	2795351	74729	3 %
1000	0.01450	8387	0.93	2726837	135661	5 %
1750	0.01450	7332	0.81	2447091	184550	8 %
2500	0.01450	6530	0.72	2375273	207636	9 %
5000	0.01450	7955	0.88	2643728	271612	10 %
20000	0	9450	1.04	3192788	1134455	36 %
20000	0.00723	7563	0.84	2453021	457390	19 %
20000	0.01450	6571	0.73	2345844	332270	14 %
20000	0.07400	7007	0.77	2676612	128345	5 %
20000	0.15200	7301	0.81	2595398	59499	2 %
20000	0.32193	7727	0.85	2930155	27323	1 %

Figure 4. Maps' evolution along a volumetric mapping mission with two robots. Each row shows a snapshot of the map of each robot at a different instant time t_k and entropy level $H(C\,|M_k)$. The time $t_k(1)$ that a single robot would need to obtain a map with the same entropy is shown on the bottom-right of the maps of robot 2. The maps' resolution is ε = 0.1 m. The pictures' scale is such that each represented arrow is equivalent to a real length of 1 m. For the presented case, s_{kmax} = 2500 and I_{min} = 0.1520.

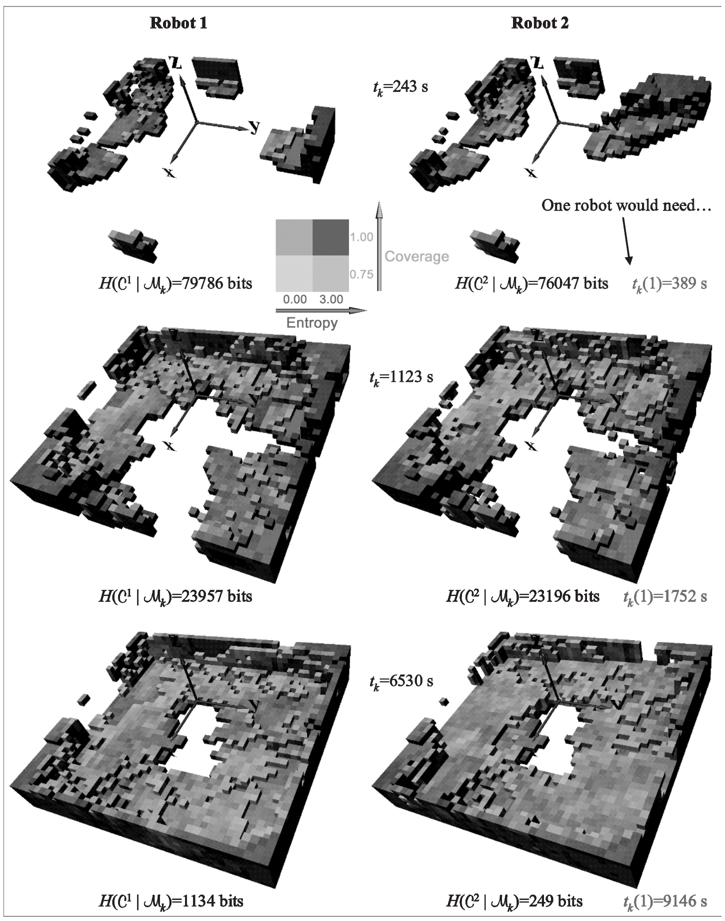


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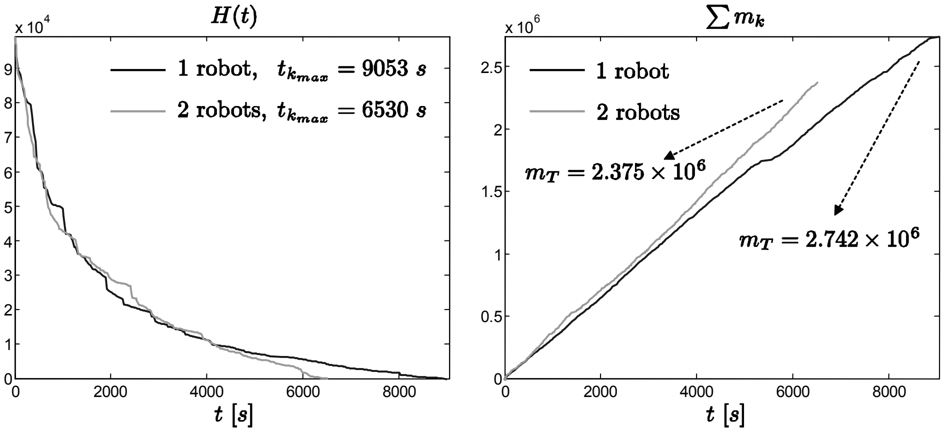
Figure 5. Comparison of a volumetric mapping mission using a single robot or two robots: Entropy of the map along the mission (left) and cumulative number of processed measurements along the mission (right). For the presented case, I_{min} = 0.0145 and s_{kmax} = 2500.



information theoretic concept. Robots use the information utility measure to communicate to other robots only sensory information that is indeed useful.

Results obtained within experiments with mobile robots equipped with stereo-vision demonstrated the validity of the presented formalism. More specifically, it was proven that a team of cooperative mobile robots is able to build a map of the environment in much less time than a single robot, as a result of using judiciously communication resources.

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KEY TERMS

Awareness: The extent to which a robot is aware of the state and goals of other robots of a multi-robot system.

Communication: Interaction involving two or more entities that exchange information, especially information that is relevant to the involved entities.

Cooperation: Joint behavior of a group of similar but not necessarily homogeneous entities which interact through different forms of communication, whether implicit or explicit, so as to barter resources and information and carry out collective missions that are not usually feasible by a single entity, or wherein a team may attain better performance.

Distributed Control: A control paradigm for multirobot systems whereby every robot participates in the team's decisions, in the absence of any central controller or hierarchy.

Information Utility: How much a piece of information is relevant to the context it refers to and how much it differs from other similar pieces of information (non-redundancy) and contributes to reduce uncertainty.

Multirobot System: A set of intelligent and autonomous mobile robots that are assumed to cooperate in order to carry out collective missions.

Volumetric Map: A representation model which integrates noisy measurements obtained with range sensors at different instant times or locations, so as to accumulate statistical evidence about the occupancy of a 3-D environment.