Proceedings Book

40th International Symposium on Robotics

Edited by:

Luis Basañez - Raúl Suárez - Jan Rosell

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Edited by:

Luis Basañez - Raúl Suárez - Jan Rosell

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Foreword

Since the first International Symposium on Industrial Robots (ISIR) held in Chicago in 1970, Robotics has experienced an important evolution and has extended its field from the industrial manufacturing operations to different kind of services useful to the well-being of humans and equipment like domestic tasks, entertainment, handicap assistance, inspection and maintenance, surgery and therapy, and public relations, among many others. This is the reason for the change of the symposium title that becomes, from 1998, International Symposium on Robotics (ISR).

Despite the high effort done in research and development, important aspects of robotics, both industrial and service, are still open challenges: better control performance, more and more efficient sensors and sensory systems, friendly and higher level programming, error recovery, real autonomy, efficient navigation, coordinated and networked robots, among others.

The following pages show a sample of these efforts made by the scientific and technical international community to respond to these challenges. More than fifty papers by experts from 11 countries have been selected by the International Programme Committee (IPC), made up of relevant persons from the academic and the industrial worlds. The scope of the papers ranges from robot modeling and control to human robot interaction, through topics like planning, robot vision and cognitive robotics.

The ISR has also become the annual mandatory meeting of industrial and applied oriented people involved in robotics and advanced automation. This fact is reflected in the significant number of papers dealing, for instance, with new robot applications, service robotics and aerial robots. In addition to the scientific-technical sessions, ISR'09 also offers to the participants several special sessions, not included in this book, dedicated to industrial sectors (aerospace, food), successful technology transfers, new and innovative products, and research strategies and funds opportunities in different geographic areas.

For the second time Barcelona, the great Mediterranean city, hosts the ISR (the first time was the 23rd ISIR in 1992). Now the ISR reaches the 40th symposium of the series and the Spanish Robotics Association (AER-ATP) has the honor and the privilege of organizing the event and to welcome the robotics community attending the ISR'09.

We hope that, in the nowadays difficult economic situation, the 40th ISR will contribute, at least in a modest way, to the progress of our society and the understanding of the people of different countries.

Luis Basañez
Raúl Suárez
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An Hybrid Architecture for Multi-Robot Integrated Exploration ⋆

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Abstract: In this paper we present an hybrid approach to the multi-robot exploration problem. The model started from a reactive system. As stated by many authors, these systems have an inconvenient, the occurrence of local minima. Restricting the model to the expected safe zone of the robot we avoid the presence of local minima. At the same time, a planner builds up a decision tree in order to decide between exploring the current expected safe zone or traveling to another one. Several simulations demonstrate the validity of the approach.

1. INTRODUCTION

Exploration is the task of covering an unknown area by a mobile robot or a group of robots. Usually, they build a model of the environment at the same time. Some applications of exploration are automated surveillance, search and rescue services or map building of unknown environments as, for example, in planetary missions. The utilization of a team of cooperative mobile robots is an advantage: the exploration time is reduced and the precision of the maps is improved because of the redundancy of measurements.

Exploration techniques work basically using the frontier concept introduced by Yamauchi [1997]. Relying on the value for each cell in a probability occupancy grid map (Moravec and Elfes [1985]), the cells can be classified as free, occupied or unknown. Frontier cells are defined as the free cells that lie next to an unknown cell.

A group of exploration methods are deliberative and they employ path planning techniques in order to direct the robots to the frontier cells (Yamauchi [1998], Simmons et al. [2000], Burgard et al. [2005], Zlot et al. [2002]). They differ in the coordination strategies used to assign a frontier to each robot: the robots can go to the nearest frontier (Yamauchi [1998]) or they can follow a cost-utility model to make their assignments. Normally, the cost is the length of the path to a frontier cell, whereas utility could be understood in different ways: Simmons et al. [2000] consider the utility as the expected visible area behind the frontier, Burgard et al. [2005] consider in the utility function the proximity of frontiers assigned to other robots. Zlot et al. [2002] suggest using a market economy where the robots negotiate their assignments.

Another group of exploration techniques are reactive and they commonly make use of potential fields (Arkin and Diaz [2002]). Potential field based exploring methods take into account a set of behaviours to generate a resultant potential field. The most common behaviours in exploration are attraction to frontiers and repulsion from obstacles and other robots. This leads to the avoidance of other robots and collisions and also improves the exploration by dispersing the robots. As stated by many authors, the main drawback of this technique is the occurrence of local minima in the potential field, which may trap the robot and block the exploration process. A common solution to this problem is to plan a path to a frontier cell in order to get the robot out from the local minimum (Lau [2003]).

The most common architecture in exploration is the hybrid deliberative/reactive. However, in the most of these approaches, the exploration is mainly directed only by one of these two processes. In this sense, when we talk about a deliberative exploration method, the exploration is planned by a deliberative process but there is a reactive low level layer to safely control the robots. And when we talk about a reactive exploration method the exploration is carried out by the inclusion of exploration reactive behaviours, however they usually include a simple high level layer that triggers different configurations of behaviours. By contrast, in our hybrid architecture, both, reactive and deliberative, processes are oriented to the exploration and both have the same level of importance in the exploration. This way, our algorithm has the main advantages of both techniques.

Generally, Simultaneous Localization and Mapping (SLAM) techniques are employed to build the map during the exploration. They allow to build a map that describes the environment while simultaneously using that map to localize the robots. However, the result obtained by the SLAM algorithm strongly depends on the trajectories performed by the robots (Stachniss et al. [2005]). Typical exploration algorithms do not take localization uncertainty into account and direct the exploration in order to minimize the distance traveled while maximizing the information gained. When the robots travel through unknown environments, the uncertainty over their position increases and the construction of the map becomes difficult. Returning to previously explored areas or closing loops reduces the uncertainty over the pose of the robots and improves the

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SLAM process. This idea has been previously exploited by other authors (Feder et al. [1999], Bourgoult et al. [2002], Makarenko et al. [2002], Sim et al. [2004], Stachniss et al. [2005]) and is commonly denoted as *Integrated Exploration* or SPLAM (Simultaneous Planning Localization And Mapping). With these techniques the robots explore the environment efficiently and also consider the requisites of the SLAM algorithm.

In this paper we present an hybrid solution to the multi-robot integrated exploration problem. Section 2 explains the advantages of this hybrid model. In Section 3 the architecture developed is explained. Section 4 show the experiments carried out to test the method and their results. We conclude in Section 5.

2. REACTIVITY AND DELIBERATION: THE HYBRID APPROACH

The point of departure of this paper is the approach presented in Juliá et al. [2008a]. We showed in this paper a reactive exploration method based on the potential field generated by the combination of several basic behaviors. The main drawback of this method is the appearance of local minima in the potential field. The origin of these local minima is mainly the presence of points of attraction behind the obstacles. The solution to this problem is to plan a path to a frontier cell when a local minimum is detected near the robot (Juliá et al. [2008b]). Being able to detect and escape from this situations avoids that the robots get blocked by the local minima and thus the exploration process can be finished. This reactive system was proved as a valid approach to multi-robot exploration.

However, local minima have a negative effect in the performance of the exploration algorithm because of the waste of time in the process of traveling to the local mininum, detecting it and planning a new route to escape from that point. We can see that this reactive approach performs well in the nearness of the robots, but in order to travel a long way a deliberative method is better. These facts lead us to an hybrid architecture.

Basically, our new approach consists in the reactive exploration of the *expected safe zone* in the proximities of the robots while a planner evaluates when to travel to other zones.

We define the *expected safe zone* of a robot as the set of free or unknown cells that can be joined with the position of the robot with a straight line without cutting any obstacle until a maximum distance d_{esz}. The concept of *Safe Zone* has been previously used in exploration algorithms (Gonzalez-Banos and Latombe [2002], Franchi et al. [2007]), but it is commonly related to the range of the sensor d_s. In this sense, we have used the expression *Expected Safe Zone* because the zone that we have defined covers a larger area than the sensor and so it includes unexplored areas.

We define a *gateway cell* as a free cell within the expected safe zone of a robot next to a free cell not belonging to this zone.

To avoid the appearance of local minima, only the cells within the *expected safe zone* are considered in reactive exploration. When all the *expected safe zone* of the robot is explored it travels to other zones through the gateway cells. This two concepts are shown graphically in figure 1.

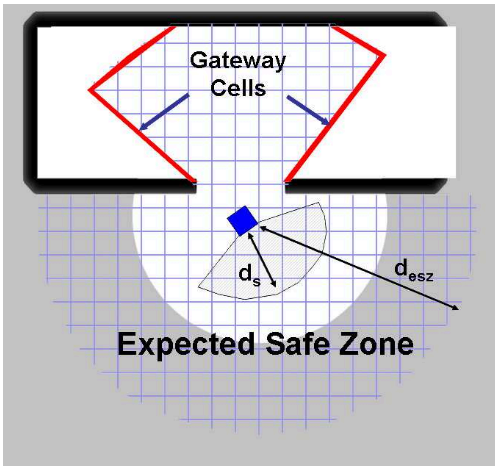

Fig. 1. Expected Safe Zone and Gateway concept

The movements of the robots will be evaluated using a two layers system. The reactive layer is the combination of several basic behaviors that include common behaviors as *go to frontier*, *avoid obstacles* or *go to gateway*. This layer operates only with cells within the *expected safe zone*. The deliberative layer controls the reactive layer enabling and disabling behaviors and setting the gateways. Thus, the deliberative layer is able to switch between several states or combination of behaviors. We work with three states that are explained in the next section:

(1) Explore Current Expected Safe Zone
(2) Change Zone
(3) Active Localization

The main task of the deliberative layer is to decide the current state. The active localization state leads the robot to past positions to recover the localization and it only works when the uncertainty in the positions of the robot is too high. When the localization is good enough, the only decision is to explore the current *expected safe zone* or to travel to another zone. This decision is made by the analysis of an exploration tree. In this tree the root node represents the current *expected safe zone* and the branches represent the *gateways* to other zones.

The main advantages of this approach are the elimination of the local minima and the delimitation of the map to the local *expected safe zone*. This fact produces that the reactive process runs in a delimited time not depending on the size of the map. We are now using a centralized SLAM technique, but it can be separated using each robot his own map and knowing the alignment between the maps. As the reactive layer only uses the local *expected safe zone* map, there is no need to have the global map in each robot. However, the deliberative layer needs information of the global map, but, in fact, only the evaluation of the branches of the decision tree is needed. Thus, a completely distributed system would work with a few communication between robots. In this paper we are focused on the hybrid architecture and this separation of the SLAM in the system is postponed to future works.

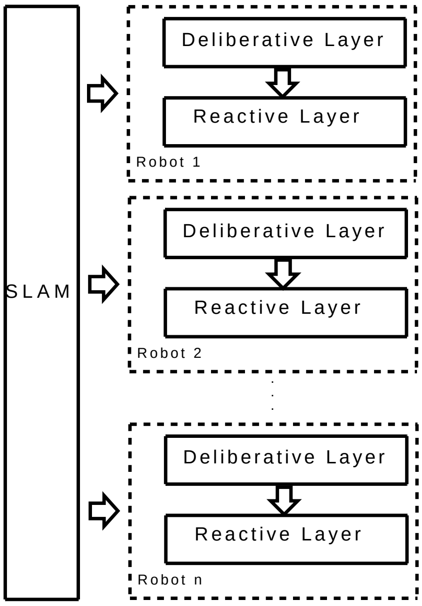

Fig. 2. Architecture

3. ARCHITECTURE

3.1 Map Building

In typical environments we can find a set of highly distinctive elements that can be easily extracted with the sensors of a robot. These elements are typically called landmarks. In our application, we assume that the robots are able to detect a set of distinctive 3D visual landmarks and they are able to obtain relative measurements to them using stereo cameras. These landmarks can be extracted as interest points found in the images of the environment (Mozos et al. [2007]). The robot team is able to build a map with a vision-based technique consisting on a particle filter approach to the SLAM problem, known as FastSLAM (Thrun et al. [2004]).

However, landmark based maps do not represent the free or occupied areas in the environment. This is the reason why we make use of an auxiliary low resolution grid map where to represent the free, occupied and unknown state of the space using the information of a sonar. We define the frontier cells as free cells that lie next to an unexplored cell.

The uncertainty in the localization of the robots can be estimated using the dispersion in the positions of the robots between the different particles of the filter. We compare this dispersion with two thresholds in a hysteresis loop to determine when the robot is well or bad localized. In order to recover a good localization, we need to save the past poses of the robots when they were well localized. In this sense, we use a binary grid map where to mark all those positions when the dispersion in the position of the robot is below the low threshold.

These maps are built by a centralized SLAM process. Besides, each robot has a reactive process and a deliberative process running concurrently with access to the maps created by the SLAM process. Figure 2 shows this model.

Table 1. Forces defined for each behavior

Go to unexplored areas:	$\boldsymbol{F}_k^1 = \frac{1}{M_U}\sum_{i=1}^{M_U} \frac{\boldsymbol{s}_i-\boldsymbol{p}_k}{r_{i,k}^3}$
Go to frontier:	$\boldsymbol{F}_k^2 = \frac{1}{M_F}\sum_{i=1}^{M_F} \frac{\boldsymbol{s}_i-\boldsymbol{p}_k}{r_{i,k}^3}$
Avoid other robots:	$\boldsymbol{F}_k^3 = \frac{1}{X}\sum_{j=1}^{X} -\frac{\boldsymbol{p}_j-\boldsymbol{p}_k}{r_{j,k}^3}$
Avoid obstacle:	$\boldsymbol{F}_k^4 = \frac{1}{M_O}\sum_{i=1}^{M_O} -\frac{\boldsymbol{s}_i-\boldsymbol{p}_k}{r_{i,k}^3}$
Go to gateway:	$\boldsymbol{F}_k^5 = \frac{\boldsymbol{q}_g-\boldsymbol{p}_k}{r_{g,k}}$
Go to precise poses:	$\boldsymbol{F}_k^6 = \frac{1}{M_P}\sum_{i=1}^{M_P} \frac{\boldsymbol{s}_i-\boldsymbol{p}_k}{r_{i,k}^3}$
M_U:	Number of unexplored cells.
M_F:	Number of frontier cells.
M_O:	Number of obstacle cells in the range.
M_P:	Number of precise pose cells.
X:	Number of robots.
$\boldsymbol{s}_i$:	Position vector of the i-th cell.
$\boldsymbol{q}_g$:	Position vector of the gateway g.
$\boldsymbol{p}_j$:	Position vector of the j-th robot.
$\boldsymbol{p}_k$:	Position vector of the k-th robot.
$r_{i,k}$:	Distance from i-th cell to robot k.
$r_{j,k}$:	Distance from robot j-th to robot k.
$r_{g,k}$:	Distance from gateway g to robot k.

3.2 Reactive Layer

Our approach to the problem of multi-robot exploration consists of six basic behaviours whose composition results in the trajectory of each robot in the environment:

Go to unexplored areas: Each unexplored cell attracts the robot.

Go to frontier: This behaviour attracts the robots to frontier cells since these are the cells that give way to areas of interest.

Avoid other robots: This behaviour results in a repulsive force between robots that normally allows to spread the robots around the environment.

Avoid obstacle: Each cell within a specific range that is identified as belonging to an obstacle, applies a repulsive effort over the robot. This range allows to easily adjust the system.

Go to gateway: This behavior attracts the robot to a gateway cell in order to access to other zones.

Go to precise poses This behavior attracts the robot to cells marked as low dispersion in the map.

Table 1 shows how the forces are calculated for each behaviour. Only the cells within the *expected safe zone* of the robots are used in the determination of each force. The resulting force of the combination of these behaviours on each robot constitutes a vector that indicates the trajectory of the robot to optimize the exploration process. The composition of the behaviours is carried out taking into account a set of weights k_i whose value is experimentally deduced. Besides, each behaviour can be enabled or disabled by the planner. Figure 3 shows the composition of the reactive model.

3.3 Deliberative Layer

The planner in the deliberative layer decides the state in which the reactive layer has to operate. Table 2 shows the three states and the behaviors that are enabled in each one.

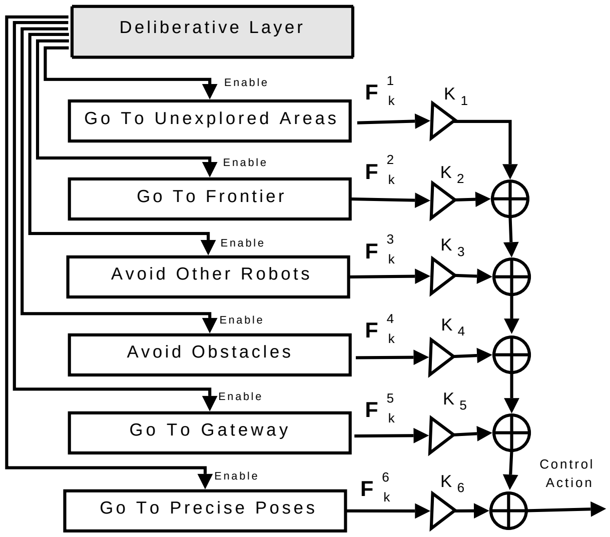

Fig. 3. Reactive Model

Table 2. States

State	Behaviors
1. Explore Current Expected Safe Zone	Go to unexplored areas Go to frontier Avoid other robots Avoid obstacle
2. Change Zone	Go to gateway Avoid obstacle
3. Active Localization	Go to precise poses Avoid obstacle

In order to have a great independence of the considered environment, we work with a very simple set of general states. This way, we do not particularize the states too much. The evaluation of an *Exploration Tree* decides the transition between these states.

Creating the Exploration Tree The first step to decide the current state is the creation of the Exploration Tree. Algorithm 1 explain how to create this tree. The tree consist of two types of nodes: branches, that are associated to gateway cells, and leaves that are related to the important cells for the exploration. In this sense, when the robot is well localized (in the hysteresis loop explained in Section 3.1), the leaves are associated to frontiers and, when it is bad localized, the leaves are associated with past precise pose cells. Each node has a position, a spatial zone associated and a cost.

In order to create the tree, we add the root node to the tree with the current position of the robot. We have to determine the expected safe zone in this position. Next step is determining the gateway cells within the expected safe zone. The gateway cells found are grouped by proximity and a new branch is added to the tree for each clustered gateway. We proceed in the same way with frontiers or precise past pose cells depending on the current state of localization of the robot. This time, we will add a leaf for each frontier or precise past pose cell. The cost of the new branches and leaves is the sum of the cost of the previous node and the distance between the position of the previous node and the position of the derived branch or leaf. This process is repeated selecting the low cost branch. It is important that the previously processed zone

Algorithm 1 Exploration Tree Creation Algorithm

```
Add root node to the tree in the position of the robot
Associate the expected safe zone to the root node
Look for gateways in safe zone → add branches
if robot is well localized then
    Look for frontiers in safe zone → add leaves
else
    Look for precise cells in safe zone → add leaves
end if
Add expected safe zone to processed zone
repeat
    Select next low cost branch
    New zone = expected safe zone from branch
    Take the processed zone away from new zone
    Associate new zone to branch
    Look for gateways in new zone → branches
    if robot is well localized then
        Look for frontiers in new zone → leaves
    else
        Look for precise cells in new zone → leaves
    end if
    Count robots in the new zone
    Add new zone to processed zone
until no remaining branches
for all leaf in tree do
    new zone = expected safe zone from the leaf
    if robot is well localized then
        Count unexplored cells in new zone
    else
        Count precise cells in new zone
    end if
end for
```

is subtracted from each new zone considered in order to expand the tree and not considering the previously analyzed zones. The process continues selecting the next low cost remaining branch until all the branches in the tree has been processed and no more gateways are detected. The cost is cumulative from each branch to the derived nodes. For each branch analyzed we have to check its associated zone looking for other robots. Once the tree is developed, we have to count the expected number of accessible interest cells from each leaf. In case of bad localization the interest cells are the past precise pose cells and in case of good localization the interest cells are the unexplored cells.

Evaluating the Exploration Tree We have a cost and a number of interest cells for each leaf. This way, we can give each leaf a value.

$$V(n_L) = \frac{I_{n_L}}{C_{n_L}^2}, \tag{1}$$

where $V(n_L)$ is the value of the leaf node n_L, I_{n_L} is the number of interest cells in the node and C_{n_L} is the cost to arrive to this node. This value is proportional to the number of interest cells and inversely proportional to the square of the cost.

This values are back-propagated until the root node choosing the maximum of the values of the child nodes in each branch divided by the number o robots in the associated zone plus one. This way, the branches where other robots are present reduce their values. Therefore, the value for each branch can be expressed as:

$$V(n_B) = \frac{max_i V(n_B^i)}{B_{n_B} + 1}, \qquad (2)$$

being $V(n_B)$ the value of the branch node n_B, n_B^i the set of child nodes of n_B and B_{n_B} the number of robots in the zone associated to the node.

The decision of the current state is made comparing the value for the first level nodes. Notice that these values are not affected when there are other robots in the current expected safe zone. This way, if two robots has very close positions, possibly they will have a similar tree with similar first level values. To achieve a better coordination we use a corrected value for the first level nodes:

$$V_c(n_1) = V(n_1) \prod_j d^2_{n_1, r^j}, \qquad (3)$$

being $V_c(n_1)$ the corrected value for the first level node n_1, $V(n_1)$ the normal value for node n_1 and d_{n_1,r^j} the distance between node n_1 and robot r^j, where r^j is the set of robots in the current expected safe zone. Thus, the nodes that are far away from other robots increase their values.

The final decision is made taking into account the corrected value for each node in the set of the first level nodes n_1^k and the localization state of the robot. These are the three possible cases:

- *Explore Current Expected Safe Zone:* When localization is good and the node of maximum value of n_1^k is a leaf.
- *Change Zone:* When the node of maximum value of n_1^k is a branch. We have to set the gateway of *go to gateway* behaviour to that node position.
- *Active Localization:* When localization is bad and the node of maximum value of n_1^k is a leaf.

4. EXPERIMENTS AND RESULTS

The method was proved in simulation with different groups of robots and different scenarios. The scenarios used in the test are shown in Figure 4. Both scenarios represent hypothetical real places with dimensions of 20 x 25m. Assuming that SLAM process runs in fixed time steps, we analyze the exploration time measured as the SLAM time steps until the exploration is finished. The exploration stops when the best first level node value in the planner is zero. The map error is measured as the RMS error obtained between the positions of the landmarks in the visual map generated and their real positions.

The results of the simulation are shown in Figure 5. As we can see, the time decreases when the number of robots grows. We can observe that *scenario 1* allows a better coordination because of the short corridor that can be rapidly explored. Thus, a lot of frontiers and gateways are easily added to the system and the coordination improves.

The error in the visual landmark map obtained is small in relation with the dimensions of the explored zone. We

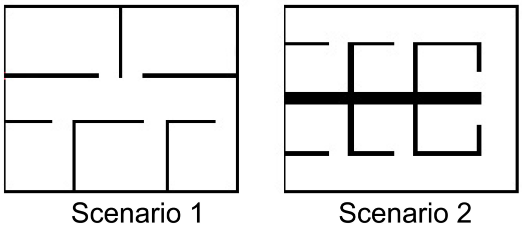

Fig. 4. Scenarios

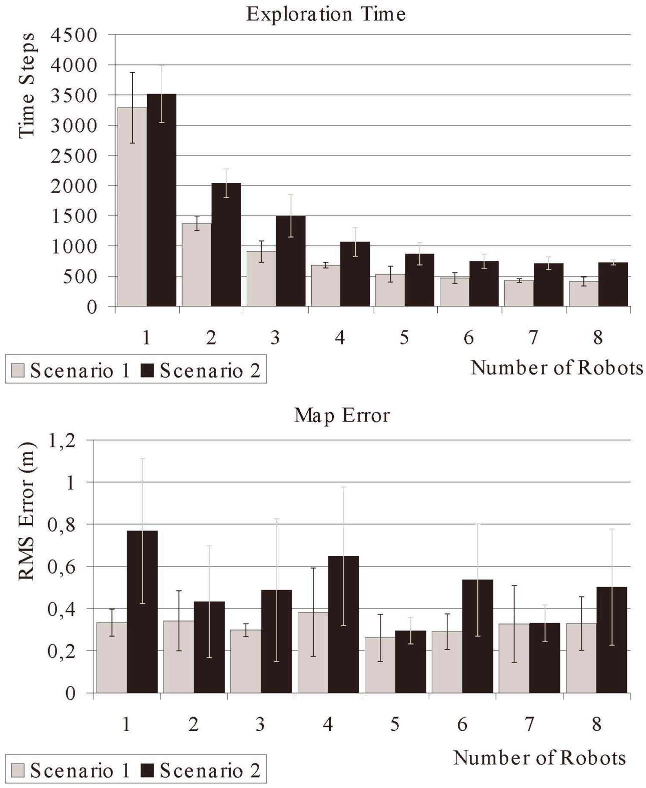

Fig. 5. Results

use a finite number of particles in the SLAM filter that is proportional to the number of robots. Furthermore, the SLAM algorithm is affected by the number of robots in two ways. In the one hand, as the number of robots grows, more observations are added to the system and the robots has to cover a minor area. Thus, the results should be better. On the other hand, despite of the increasing number of particles in the filter proportionally to the number of robots, each particle is a worst representation of the state of the robot because they represent the position of all the robots in the system. Besides, the system includes the active localization state in order to recover the localization when the uncertainty in the position of the robots is high. As a result, we can not observe a clear dependence of the error with the number of robots.

Analyzing the planner, each robot made 18 transitions between states in average. 52% of the time they work in the *Change Zone* state, 42% of the time they work in the state of *Exploring Current Expected Safe Zone* and 6% of the time they use the *Active Localization State.*

5. CONCLUSIONS

Taking a reactive system as point of departure, an hybrid approach to the multi-robot exploration problem has been developed. The reactive system was based on the potential field generated by several basic behaviors. As stated by many authors, potential field based methods have an inconvenient, the occurrence of local minima. However, restricting the model to the expected safe zone of the robot we avoid the presence of local minima. In order to guarantee the conclusion of the exploration some planning is needed. For these reason, our system is made of two parts: a reactive layer and a deliberative layer that controls the reactive layer. The reactive layer operates with the basic behaviors in the expected safe zone. A planner in the deliberative layer builds up a decision tree in order to decide between exploring the current expected safe zone or traveling to another one. An algorithm to create and evaluate the Exploration Tree has been developed. Besides, the planner considers also the uncertainty in the location of the robots in order to return to previously explored places when the uncertainty becomes significant. This fact improves the quality of the resulting map. Several simulations have been presented that demonstrate the validity of the approach.

As future works, we consider the extension of the approach in real dynamic environments, adding techniques to learn automatically the multiple settings of the system. We will develop a full distributed system by separating the SLAM process between the robots. Inter-robot communication and mechanisms for meeting the robots to align their maps will be added. Semi-operated models that integrate the commands expressed by a human operator in the exploration task will also be studied.

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