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Mechanisms for collaborative teleoperation with a team of cooperative robots

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Abstract

Purpose – This paper aims to present a teleoperation system that allows one to control a group of mobile robots in a collaborative manner. In order to show the capabilities of the collaborative teleoperation system, it seeks to present a task where the operator collaborates with a robot team to explore a remote environment in a coordinated manner. The system implements human-robot interaction by means of natural language interfaces, allowing one to teleoperate multiple mobile robots in an unknown, unstructured environment. With the supervision of the operator, the robot team builds a map of the environment with a vision-based simultaneous localization and mapping (SLAM) technique. The approach is well suited for search and rescue tasks and other applications where the operator may guide the exploration of the robots to certain areas in the map.

Design/methodology/approach – In opposition with a master-slave scheme of teleoperation, an exploration mechanism is proposed that allows one to integrate the commands expressed by a human operator in an exploration task, where the actions expressed by the human operator are taken as an advice. In consequence, the robots in the remote environment choose their movements that improve the estimation of the map and best suit the requirements of the operator.

Findings – It is shown that the collaborative mechanism presented is suitable to control a robot team that explores an unstructured environment. Experimental results are presented that demonstrate the validity of the approach.

Practical implications – The system implements human-robot interaction by means of natural language interfaces. The robots are equipped with stereo heads and are able to find stable visual landmarks in the environment. Based on these visual landmarks, the robot team is able to build a map of the environment using a vision-based SLAM technique. SONAR proximity sensors are used to avoid collisions and find traversable ways. The robot control architecture is based on common object request broker architecture technology and allows one to operate a group of robots with dissimilar features.

Originality/value – This work extends the concept of collaborative teleoperation to the exploration of a remote environment using a team of mobile robots.

Keywords Remote control systems, Robotics, Interactive devices, Search and rescue

Paper type Technical paper

1. Introduction

Lately, a large number of applications have emerged that require the utilisation of groups of mobile robots. In these applications, the robots must be able to proceed autonomously in a coordinated manner to complete a particular mission. As an example, we can think of a group of robots exploring an office environment. In this situation, the robots must arrange their movements so that they can create a correct map of the environment. For example, in Vazquez and Malcolm (2004), a group of robots cooperate to complete a task in the remote environment. However, we could think of a great quantity of critical tasks where the human participation is advisable. For example, in a search and rescue mission, a human operator may guide the robot team and suggest to explore areas where the victims could be localized with more probability (Bruemmer *et al.*, 2002). In addition, as the robots are placed in more indeterministic environments, it becomes clear that the interaction with humans and the need to establish mechanisms that allow to work in a coordinated way, sharing the same space and objectives.

In a classical teleoperation schema, the human operator controls directly the robot, that performs a particular task in the remote environment (Vertut and Coiffet, 1985). A more sophisticated approach consists of handling and supervising an environment shared by multiple users. This is the scheme analysed in Monferrer and Bonyuet (2002), where multiple users, each one at a different location, work simultaneously on different activities. Also, in Goldberg *et al.* (2000) a distributed group of users simultaneously teleoperate an industrial robot arm via internet. A client-server system is described that facilitates the cooperation of several simultaneous users to share a single robot resource.

In other teleoperation systems, the interaction between the human and the robot or robots in the remote environment is achieved through high-level dialogues using natural language commands (Hoffman and Breazeal, 2004). Fong *et al.* (2001, 2003) present a set of tools that allow to improve the human-robot interaction in a vehicle application. In the control scheme proposed, a human and a robot interact to perform tasks and to achieve goals. Instead of a supervisor dictating to a subordinate, the human and the robot engage in dialogue to exchange ideas and resolve differences.

Finally, there are other teleoperation systems where a collaboration between the remote and local environment is stablished. This scheme is oftenly denoted collaborative teleoperation. In this case, the collaboration can be

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understood as a fellowship association in which the robots and the human operator share the same objectives and act regarding to their possibilities and prior knowledge. In this collaborative scheme, the robot or robot team may decide how to use a human order: they may obey when the order suits the requirements and they can modify it when considered inappropriate. In this sense, the commands produced by the human operator are taken as and advice, and therefore the robot team has more freedom in the operation than in a classical teleoperation scheme. For example, we can find applications where it is advisable that a human operator could suggest to explore some specific areas of the remote map. This is the case, for example, of search and rescue applications, where it is necessary that the exploration is guided by a human operator which uses its experience and prior knowledge to explore particular areas in the environment and look for trapped victims. In this way, the exploration of the robot group is not fully autonomous, and there exists the possibility to give commands to the robots as a whole.

In this paper, we present a collaborative teleoperation system that includes human-robot interaction by means of natural language interfaces, allowing to teleoperate multiple mobile robots in unknown unstructured environments. In order to show the capabilities of the collaborative teleoperation system, we present a task, where the cooperation between human and robots takes part. In the application, the operator collaborates with a robot team to explore a remote environment in a coordinated manner. The rest of the paper is arranged as follows: Section 2 exposes the robot control architecture that is used to control the group of heterogeneous robots. Next, Section 3 explains the mechanisms used to explore an unknown environment using a team of mobile robots. In Section 4, we deal with the interaction mechanism between the human operator and the robot team. Section 5 presents results obtained after several tests performed with the system. Finally, in Section 6, we present the main conclusions and further work.

2. Robot control architecture interface

We have developed an architecture that allows the monitorization and control of a group of mobile robots with different sensorial capacities and internal architectures. It is also possible to perform cooperative tasks, since the architecture offers a high-level communication layer between the robots (Payá *et al.*, 2006). Currently, the robot team is constituted by different models, in particular: 4 Wifibot robots, 3 Pioneer 3AT, and a B21r robot.

2.1 Network architecture

The communication between mobile robots with dissimilar capabilities and sensorial skills suggested the design of a network architecture that could integrate different communication technologies. The network can be divided mainly into two subnetworks:

1. Fast Ethernet-wired network where several personal computers are connected.
2. WIFI 802.11b/g network that communicates with the robots.

2.2 Communication protocols

The communication between the agents in the system is based on common object request broker architecture (CORBA) technology (OMG, 1995). The CORBA architecture offers an object-oriented metodology for the implementation of distributed applications. This standard has previously shown to be suitable to share data among teams of mobile robots (Payá *et al.*, 2006). We can distinguish two main capabilities in CORBA:

1. *The separation between interface and implementation.* This separation is achieved by an interface language called Interface Definition Language (IDL). Mainly, each interface defines a service that is implemented by a software component. Frequently, an object (a C++ object in our implementation) implements a series of interfaces, which allow to communicate data from the sensors and commands to the robots.
2. *The transparency to access the implementation.* Each of the objects can be accessed by an inter-operable object reference (IOR), that can be thought as an unique address in the system.

In Figure 1, we show the main elements involved in the communication and the operation of the system. The main components in the system are:

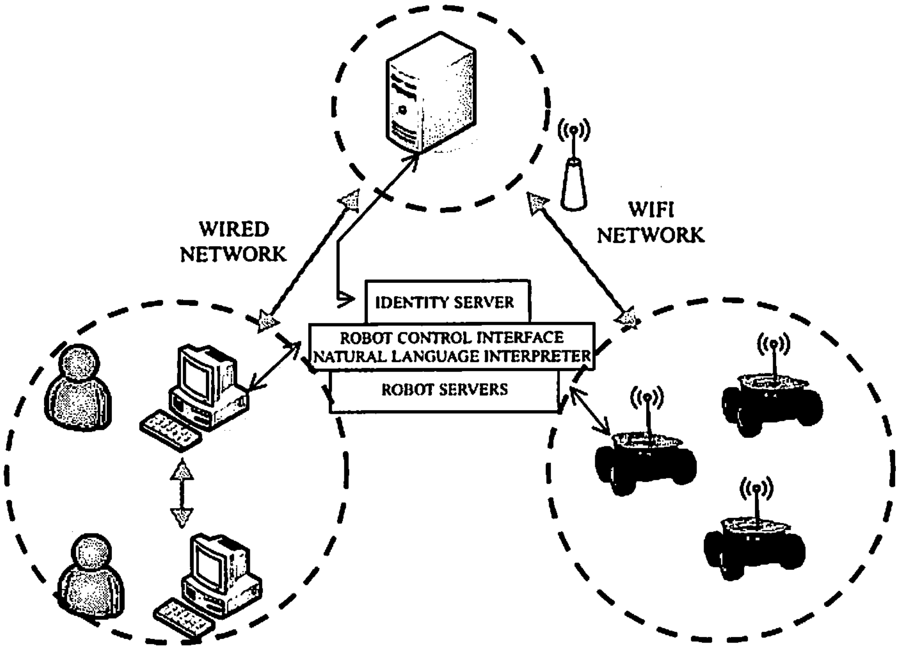
Identity server. This is the most important element in the system, since it stores the state of every other component in the system. This component is executed on a PC connected to the wired network. The static IP address of this computer must be known by each element that wants to connect to the system. However, this is the only requirement that allows to stablish all the communications in the system. The identity server maintains a list of all the robots that are active in the system and which are the interfaces available on each one. In addition, each one of the robots (identified by a unique name in the network) implements a series of CORBA interfaces, associated mainly with the sensors that carries. This scheme allows to have a variable number of robots active in the system.

Robot servers. Several servers are executed onboard of each robot that directly access their sensors (cameras, motors, laser sensors). The interfaces implemented on them depend on the concrete sensors that it carries. Each sensor is associated with a CORBA interface and identified by an IOR string.

Natural language interpreter. This component has two main purposes. First, it uses the IBM ViaVoice speech recognizer to process voice commands given by the human operator. Second, it processes the former commands with a natural language interpreter, in order to obtain the commands that can be understood by the system. The commands are stored in a list that is accessed by the robot control interface. Once a command is processed, it is removed from this list.

Robot control interface. The robot control interface is the component that allows the interaction of the robot team with a human operator. It is executed on a computer connected to the wired network. This program communicates with the identity server and the robot servers. It allows a human operator to give commands to the robot team and to observe the data acquired by one of the robots. The robot control interface requests periodically the data from the sensors of each robot in order to build the map, as described in Section 3. At each time step, the interface computes the best map and the pose of each of the robots in the system.

Figure 1 Communication and system architecture of the collaborative control system proposed



In addition, periodically, it requests commands from the natural language interface. When a voice command has been issued by the operator, the robot control interface receives it and the order given by the operator is taken into account. Based on the poses of the robots and the commands given by the human operator, the interface computes the particular commands that must be performed by each one of the robots as shown in Section 3.

At the starting phase of the system, the identity server must be available, since the other components attempt first to connect to this component. Once a robot server starts, it contacts the identity server, which publishes the robot name and the available interface. From this moment, the information is available and other robots and the robot control interface can access the services provided. Finally, CORBA allows to communicate different programs written with different languages and running under different operative systems. Currently, the robot servers run under Linux Debian, while the robot interface is running under Windows XP.

3. Multi-robot environment exploration

In this section, we describe the use of the robot control architecture to a particular application: the cooperative exploration of an unknown environment by a group of robots. In this task, a team of robots cooperate with a human operator to build the most correct map of the environment. A behaviour-based approach has been used with this aim. In this approach, the combination of several basic behaviours constitutes the global behaviour of the robot. This approach has been applied successfully to some tasks in collaborative robotics, including multi robot exploration, as shown in Lau (2003) and Vazquez and Malcolm (2004).

3.1 Simultaneous localization and map building

In typical environments (e.g. office-like environments), we can find a set of highly distinctive elements that can be easily extracted with the sensors of a robot (i.e. walls, corners…, etc.). These elements are commonly called landmarks. In our application, the robots detect a set of distinctive 3D points using a stereo camera system, and are able to obtain relative measurements to them. Interest points are extracted from images of the environment and used as visual landmarks (Gil *et al.*, 2006).

In order to build a map, we must know the position and orientation of all the robots with respect to a global reference system. This enables to put the observations together to build a coherent map. However, as the robots move, the uncertainty over its pose increases, due to cumulative errors in odometry systems. This poses the problem of building a map while concurrently localizing in it which is known as the simultaneous localization and mapping (SLAM) problem. In this paper, we do not concentrate on this problem, on the contrary, we use a SLAM technique known as FastSLAM (Montemerlo *et al.*, 2002) that is well suited for this application. The whole robot group builds the map simultaneously.

The success of the SLAM task depends highly on the trajectories performed by the robots, for example, returning to previously explored places decreases the uncertainty over the pose and enables to obtain a more accurate map, whereas exploring new areas improves the knowledge of the environment. In this sense, following exactly the commands issued by a human operator could result in the creation of an imprecise map that may be useless for the exploration. In consequence, in the proposed approach, the commands issued by the human operator are evaluated and the robots perform the movements that best suit both the creation of the map and the human orders.

3.2 Behavioural approach for multi-robot cooperative exploration

Our approach to the problem of multi-robot cooperative exploration consists of several basic behaviours whose composition results in the trajectory of each robot in the environment. These basic behaviours are described in this section. In Section 4, we will outline how the voice commands emitted by the operator can be taken into account to guide the movements of the robot team.

During the exploration, the area to explore is divided in a cell grid. At each moment, each cell can be classified as a free cell, obstacle cell or boundary cell (cells placed between explored and non-explored areas). All the free cells have a numerical value associated that indicates their degree of exploration, which is increased each time it falls into the field of vision of the robot, until it reaches a limit value when the cell is considered to be fully explored. The obstacle cells are detected using the information of the sonar.

Six basic behaviours have been designed to solve the problem of cooperative exploration in an optimal way. Besides, at each moment, each robot can behave according to one of two possible high-level states: explore or decrease uncertainty. The explore state allows going to new areas of the map while the robots are well localized. The decrease uncertainty state intends to lead the robot to previously explored areas when it has a relatively high uncertainty associated, thus improving their localization. The output of each state is calculated as the combination of some of the six basic behaviours. Also, the transition between both states is made according to a hysteretic model with two transition thresholds that measure the precision in the pose of the robot (particle dispersion).

3.2.1 State A: explore

The output of this state is the combination of the following basic behaviours:

Go to unexplored areas. The aim of this behaviour consists of attracting the robot to the areas of the map that are unexplored or poorly explored. Knowing the dimensions of the environment to explore and the initial pose, each cell attracts each robot with a force that depends on the degree of exploration of the cell and the distance to the robot. The resulting force of this behaviour on the robot k is the composition of the forces of every unexplored cell in the map:

$$\vec{F}_k^1 = \frac{1}{M}\sum_{i=1}^{M}\vec{f}_i = \frac{1}{M}\sum_{i=1}^{M}\frac{v - e_i}{v}\cdot\frac{\vec{s}_i - \vec{p}_k}{r^2} \tag{1}$$

Being M the number of cells in the map, $\vec{f}_i$ the force associated with the cell i, e_i the degree of exploration of the cell i, v the maximum value associated to the cell, $\vec{s}_i$ the position of the i-th cell, $\vec{p}_k$ is the position of the k-th robot and:

$$r = \sqrt{(\vec{s}_i - \vec{p}_k)^T(\vec{s}_i - \vec{p}_k)}$$

the Euclidean distance between both positions.

Go to boundary. This behaviour attracts the robots to cells that constitute the boundaries between explored and unexplored areas, since these are the cells that give way to areas of interest. Once these cells are identified, the resulting force of the behaviour on the k-th robot is calculated as follows:

$$\vec{F}_k^2 = \frac{1}{M_F}\sum_{i=1}^{M_F}\vec{f}_i = \frac{1}{M_F}\sum_{i=1}^{M_F}\frac{\vec{s}_i - \vec{p}_k}{r^3} \tag{2}$$

Being M_F the number of frontier cells in the map, $\vec{f}_i$ the force associated with the i-th boundary cell, $\vec{s}_i$ the position of the i-th frontier cell, $\vec{p}_k$ the position of the k-th robot and r the Euclidean distance between both positions.

Avoid robot. To avoid overlapping between the areas, each robot is exploring, this behaviour results in a repulsive force between robots to optimize the explored zone. The resulting force on robot k is:

$$\vec{F}_k^3 = \frac{1}{X}\sum_{j=1}^{X}\vec{f}_j = \frac{1}{X}\sum_{j=1}^{X}\left(-\frac{\vec{p}_j - \vec{p}_k}{r^3}\right) \tag{3}$$

where X is the number of robots, $\vec{f}_j$ the force exerted by the robot j, $\vec{p}_j$ is the position of the j-th robot, $\vec{p}_k$ is the position of the k-th robot and r the Euclidean distance between both positions.

Avoid obstacle. Each cell that is identified as belonging to an obstacle, applies a repulsive effort over every robot, which is inversely proportional to the square distance between robot and obstacle cell. The resulting force is:

$$\vec{F}_k^4 = \frac{1}{M_O}\sum_{i=1}^{M_O}\vec{f}_i = \frac{1}{M_O}\sum_{i=1}^{M_O}\left(-\frac{\vec{s}_i - \vec{p}_k}{r^3}\right) \tag{4}$$

Being M_O the number of obstacle cells in the map, $\vec{f}_i$ the force associated with the i-th obstacle cell, $\vec{s}_i$ the position of the i-th obstacle cell, $\vec{p}_k$ the position of the k-th robot and r the Euclidean distance between both positions.

Improve imprecise landmarks. This behaviour tries to improve the quality of the exploration of those areas where some landmarks have been extracted but whose accuracy is not high enough. A global uncertainty measurement σ^l associated to every landmark is computed based on the variance in x, y, and z directions $\sigma x^2, \sigma y^2, \sigma z^2$ in the position of the best estimated landmark. The landmarks whose error associated is over a threshold, exert an attractive force on the robot k according to the expression:

$$\vec{F}_k^5 = \frac{1}{n_t}\sum_{l=1}^{n_t}\vec{f}_l = \frac{1}{n_t}\sum_{l=1}^{n_t}\left(\sigma^l\cdot\frac{\vec{q}_l - \vec{p}_k}{r^3}\right) \tag{5}$$

being n_t the number of landmarks whose error is over the threshold, $\vec{f}_l$ the force associated with the landmark l, $\vec{q}_l$ is the position of the l-th landmark, $\vec{p}_k$ is the position of the k-th robot and is the Euclidean distance between both positions.

This way, the resulting force of the combination of those five behaviours on each robot constitutes a vector that points out the trajectory of the robot to optimize the exploration process as follows:

$$\vec{F}_k^A = k_1\cdot\vec{F}_k^1 + k_2\cdot\vec{F}_k^2 + k_3\cdot\vec{F}_k^3 + k_4\cdot\vec{F}_k^4 + k_5\cdot\vec{F}_k^5. \tag{6}$$

The composition of the behaviours is carried out taking into account a set of weights k_i whose value has been deduced experimentally.

3.2.2 State B: decrease uncertainty

In this case, a second state has been designed where the control action of the robot is the composition of the outputs of two basic behaviours, avoid obstacle, already presented, and the new behaviour go to accurate landmarks.

The behaviour go to accurate landmarks tries to improve the estimation of the position of the robot, driving it to landmarks whose position has a robust estimation. This means that the position of the landmark is very similar for all the particles used to calculate the position of the robot. Given a landmark, its position is calculated for each particle and a measure of the error ε^l is calculated using the dispersions $\varepsilon^l_x, \varepsilon^l_y, \varepsilon^l_z$ of the positions of the landmark. The resulting force is calculated as follows:

$$\vec{F}^6_k = \frac{1}{n}\sum_{l=1}^{n}\vec{f}_l = \frac{1}{n}\sum_{l=1}^{n}\left(\frac{1}{\varepsilon^l}\cdot\frac{\vec{q}_l - \vec{p}_k}{r^2}\right) \qquad (7)$$

being n the current number of landmarks in the map, $\vec{f}_l$ the force associated with the landmark l, $\vec{q}_l$ is the position of the l-th landmark, $\vec{p}_k$ is the position of the robot k and is the Euclidean distance between both positions.

Then the trajectory to follow is pointed by the vector:

$$\vec{F}^B_k = k_4 \cdot \vec{F}^4_k + k_6 \cdot \vec{F}^6_k \qquad (8)$$

This way, the output of each state can be seen as the composition of the outputs of the behaviours described, where the weights have been deducted experimentally, taking the following values:

Figure 2 shows the bird's eye views of two different exploring situations with three robots. On both charts, the weighted outputs of the behaviours and the resulting arrows are shown for each robot. In all the cases, the state A is active, except for the robot 1 on the right chart, where state B is active. Also, the landmarks that have been detected until that moment are shown, drawing their positions and uncertainties.

4. Multi-robot cooperative exploration with collaborative control

Based on the exploration method proposed in the previous section, we propose here an extension with a collaborative control system that allows the operator to interact with the robots. In typical exploration applications, the robot or robots explore autonomously the environment and choose their trajectories in order to minimize the error in the map that is being built (Burgard *et al.*, 2005). In the method presented here, the operator suggests new areas of exploration which are taken into account by the robots along with the rest of behaviours. In opposition to other approaches, the approach exposed permits the interaction between the operator and the remote agents. A cooperation between the local and the remote environment is established, that takes into account the prior knowledge of the operator and the instantaneous configuration of the environment to explore.

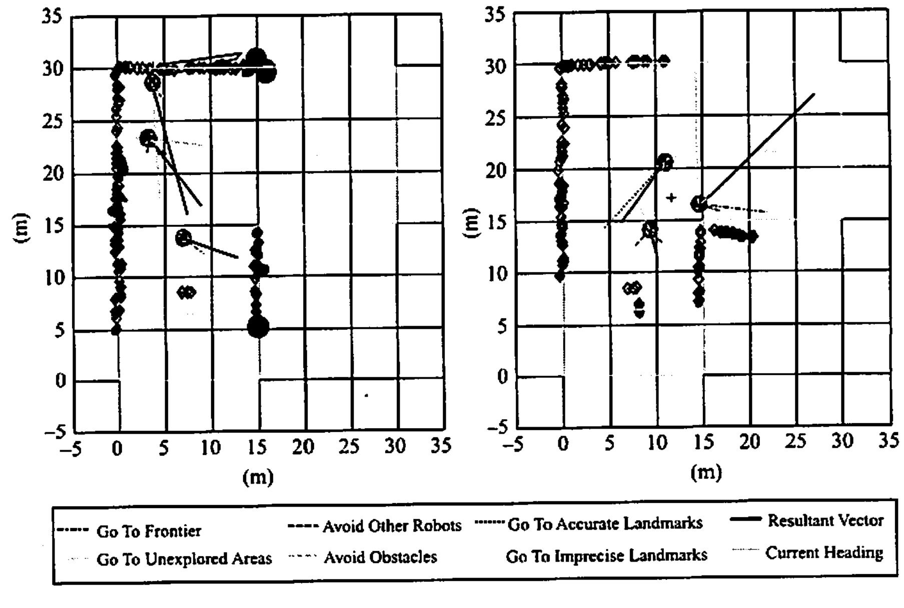
4.1 Natural language comprehension

The system is able to recognize a set of voice commands that allow to set a target point in the map. The words recognized by ViaVoice are evaluated by a grammar function that allows to interpret sentences like: "move a little more to the right" or "explore much more to the top and the left". Each of the natural expressions that can be issued by the operator is associated to a constant c_i, which models the magnitude of the displacement. For example, the constant c_1 is associated to relatively "very small" movements and the constant c_2 is associated to "small" movements. The constant $c_6 = 0$ is associated with a zero displacement in the target point. This allows the operator to maintain the interest on a particular point. These constants depend on the particular application, in our case, the concrete values used are exposed in Table II.

4.2 Representing uncertainty

The application presented here allows to direct the exploration of the robot group to an interesting area in the map. We represent the target point that should be explored by

Figure 2 Weighed outputs of the behaviours in two moments of two different exploring situations without supervision of the operator



the robot by a Gaussian distribution $N(\mu, \Sigma)$, where $\mu = (x,y)^T$ is a point in the map referred to a global coordinate system and:

$$\Sigma = \begin{pmatrix} \sigma_x^2 & 0 \\ 0 & \sigma_y^2 \end{pmatrix} \tag{9}$$

is a diagonal covariance matrix, with σ_x and σ_y representing the uncertainty in the x and y directions. In this way, if the aim of the operator is to explore a wide area in the map, this would be represented by a mean value and a big covariance matrix. When the operator desires to explore a certain point in the map we will represent it as a mean value and a low variance. In particular, we represent the Gaussian distribution by a set of samples drawn from it. This representation allows to quickly compute the attractive force of the target point. A new behaviour is created that attracts the robot to the target point. This behaviour is called "Move to target point" and works in combination with the behaviours defined in Section 3.2, affecting the state A. The force created by this behaviour on the robot k is computed as:

$$\vec{F}_k^7 = \frac{1}{N}\sum_{i=1}^{N} \vec{f}_i = \frac{1}{N}\sum_{i=1}^{N} \frac{\vec{s}_i - \vec{p}_k}{r^2} \tag{10}$$

where $\vec{f}_i$ is the force associated by the sample i, $\vec{s}_i$ is the position of the i sample drawn from $N(\mu, \Sigma)$, $\vec{p}_k$ is the position of the k robot and:

$$r = \sqrt{(\vec{s}_i - \vec{p}_k)^T(\vec{s}_i - \vec{p}_k)}$$

is the Euclidean distance between both positions.

4.3 Robot-operator interaction

We consider that at a particular time, the robot team may be exploring the environment. Then, the operator issues a command like "explore a little more to the top". The initial reference point for the robots is computed as the mean value of all the positions in the robot group. The next target point that the robots should explore is computed as:

$$\mu_{i+1} = \mu_i + (\mathbf{c}_x\mathbf{c}_y)\cdot\Sigma_i \tag{11}$$

where $\mu_i = (x,y)_i^T$ and $\mu_{i+1} = (x,y)_{i+1}^T$ is the mean value of the distribution that models the target point to explore at the time i and $i+1$, respectively, and Σ_i is the covariance matrix defined in equation (9). The vector $(\mathbf{c}_x, \mathbf{c}_y)$ defines a direction and a module, based upon the constants defined in Table I. For example, if the operator says: "Move much more to the left and a little more down" the vector would be: $(\mathbf{c}_x, \mathbf{c}_y) = (-2, 0.1)$. If the operator issues consecutively commands in time, we assume that he desires to refine the position of the point, by reducing the variance of the distribution. To do so, the variance is modified following the expression:

$$\Sigma_{i+1} = \sqrt{\Sigma_i} \tag{12}$$

In this way, the equation associated with the state A would results in the following:

$$\vec{F}_k^A = k_1\cdot\vec{F}_k^1 + k_2\cdot\vec{F}_k^2 + k_3\cdot\vec{F}_k^3 + k_4\cdot\vec{F}_k^4 + k_5\cdot\vec{F}_k^5 + k_7\cdot\vec{F}_k^7 \tag{13}$$

With this solution, the operator can easily command high displacements when he begins to emit commands and low corrections on the target point, as the robots move to desired point. In addition, the weight k_7 is modified when the operator communicates a command. In this sense, the weight is increased when the operator emits a command repeatedly, assuming that the interest on that area is high. The weight is decreased and finally is reset to zero when the operator does not emit a command for a specific time. This cancels the "Move to target point" behaviour, allowing the robot team to explore autonomously.

Table I Weights assigned to each behaviour in the two possible states

State	k_1	k_2	k_3	k_4	k_5	k_6
State A: explore	1	5	1	20	2	0
State B: decrease uncertainty	0	0	0	20	0	15

5. Experiments

In this section, we give details on a series of experiments performed with a group of mobile robots. The experiments were performed at our mobile robotics laboratory, which is an example of an office-like environment. The environment is approximately 40 × 40 m, and contains two main loops, as can be seen in Figure 2. All the experiments were supervised by a human operator, giving at each case different commands by means of natural language sentences. The constants k_i defined in equation (4) are set to the values listed in Table I. These values were obtained after several runs in different environments and human operators.

Three Pioneer3-AT robots were used in the experiments, equipped with a STH-MDCS2-VAR stereo head from Videre Design and SONAR sensors, that provide information about the obstacles in the environment. When the robots explore the environment, they observe natural landmarks and compute relative distances to them (Figure 3). Only the landmarks observed at a distance $d_{\max}$ below 4 m are considered in the SLAM algorithm. This limitation is imposed by the errors in the measurement, associated with the calibration of the stereo cameras. The field of view of the stereo set is 70°.

Three different experiments have been carried out, which simulate three different situations that could occur during the operation of the system:

1. In the first situation, the robots explore a remote environment which is completely unknown for them and meanwhile a human operator supervises the task. In this first situation, the operator does not emit any command during the exploration. In consequence, the robot team explores the remote environment in a fully autonomous manner.
2. In the second experiment, the operator interacts with the robot team, issuing commands with natural language according to his wishes. In this case, the operator is interested on a certain point in the map. After the point is selected, the operator issues commands to keep the attention on this point. The list of voice commands used in this experiment is listed in Table II.

Figure 3 Behaviour-based diagram used in the application

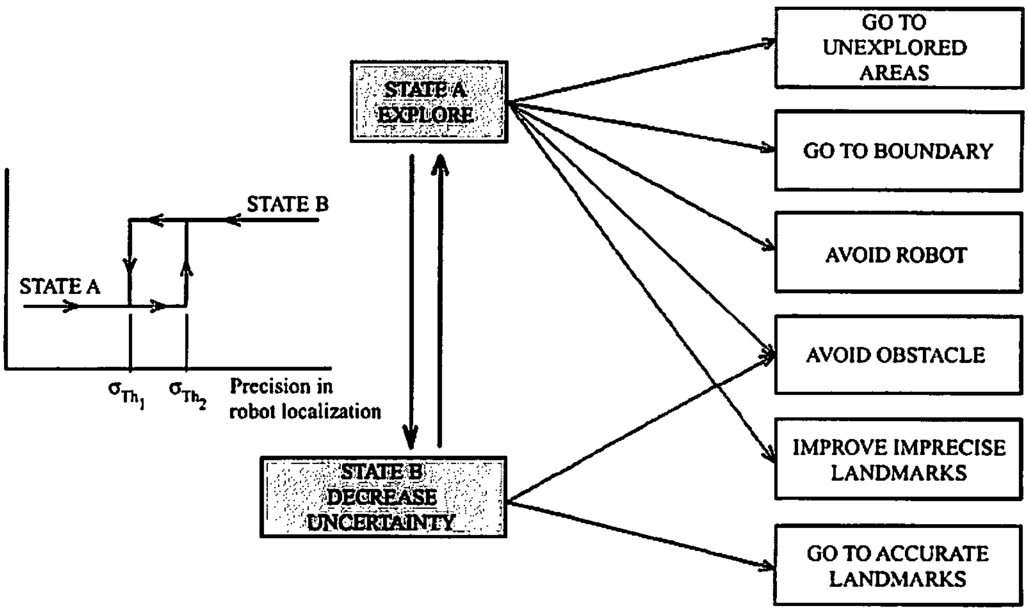


Table II Constants that model the magnitude of the displacement

Expression	c_i	Value
Move very little more to	c_1	0.66
Move a little more to	c_2	1.33
Move to the	c_3	2.0
Move more to the	c_4	2.66
Move much more to the	c_5	3.33
Go to selected point	c_6	0

3 In the third experiment, the operator, again, emits commands to suggest the exploration of certain points. In this case, the operator moves the target point in different time steps, consequently, the trajectories of the robots are computed to reflect these changes.

In Figure 4(a), we show the trajectories performed by each one of the robots in an exploration guided by the human operator; in Figure 4(b), we can see a detail of the trajectories when the state change takes place.

The results of the first experiment are shown in Figure 4(a). Here, we show the map and the trajectories followed by each one of the robots. As can be seen in the figure, each of the robots starts from a different position in the map (shown as a filled circle in the figure), and follows a different trajectory. This trajectory is computed using equations (6) and (8), taking into account the behaviours exposed in Section 4. It is worth noting that in several steps during the experiment, the robots with a high-uncertainty change to the state B (decrease uncertainty) and travel to previously explored areas, thus reducing the uncertainty in their localization. A detail of the occurrence of the state B can be seen in Figure 4(b).

In the second experiment, the operator issues a series of natural language commands. The commands are emitted consecutively and are listed in Table III. In Figure 5, we show the trajectories followed by each of the robots. As can be seen in Figure 5, the robots tend to the area proposed by the user, nevertheless, the robots achieve an agreement, taking into account the preferences of the operator and the exploration task. We can clearly observe the influence of the operator at the time when he issues a command, since the trajectories of the robots are modified by the force $\bar{F}'_k$, defined in equation (10).

Figure 4

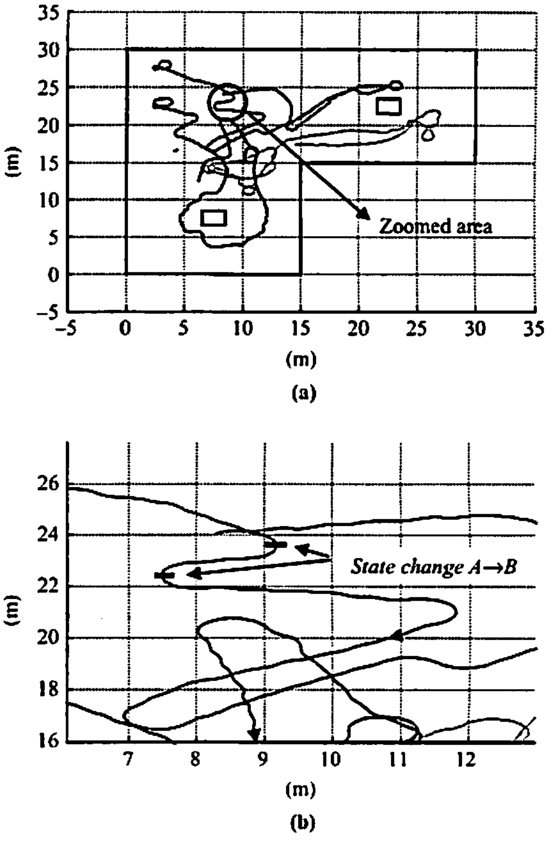


Table III Natural language commands emitted by the operator in the 2nd experiment

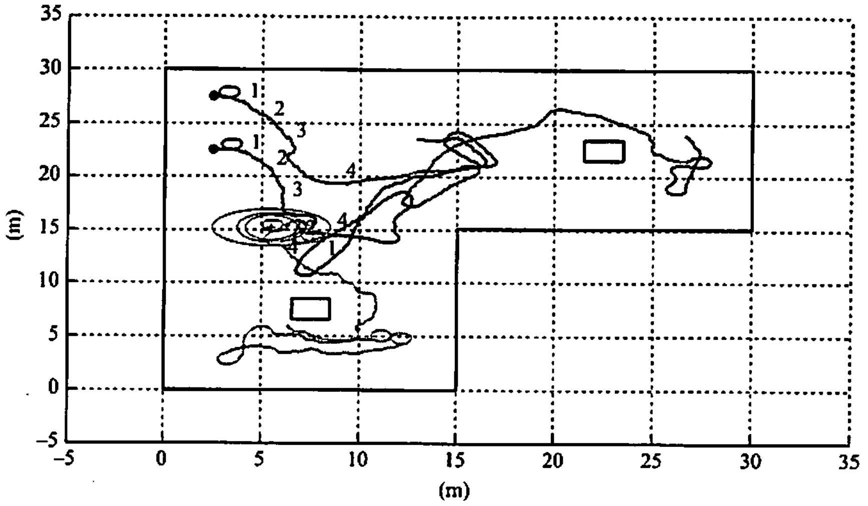
Point	Sentence
1	Go forward
2	Go to selected point
3	Go to selected point

Finally, Figure 6 shows the results of the third experiment. In this experiment, the operator emits the sentences listed in Table IV. In this case, the area where the operator desires to explore changes during the experiment. As defined in equation (12), the variance associated to the exploration target reduces with each command, allowing the operator to direct the exploration more precisely. In Figure 6, we can observe the evolution of the position associated to the target point. Figure 7(a) shows the uncertainty associated with the target point. We can clearly see that the uncertainty is reduced as the operator issues a command. The uncertainty is only reduced in the direction of change, and maintained in the other direction. In Figure 7(b), the weight k_7 is shown. This weight is associated with the interaction of the operator with the robot team. This weight is modified at each time step: it is increased each time the operator issues a command, and it is

Table IV Sentences emitted by the operator in the 3rd experiment

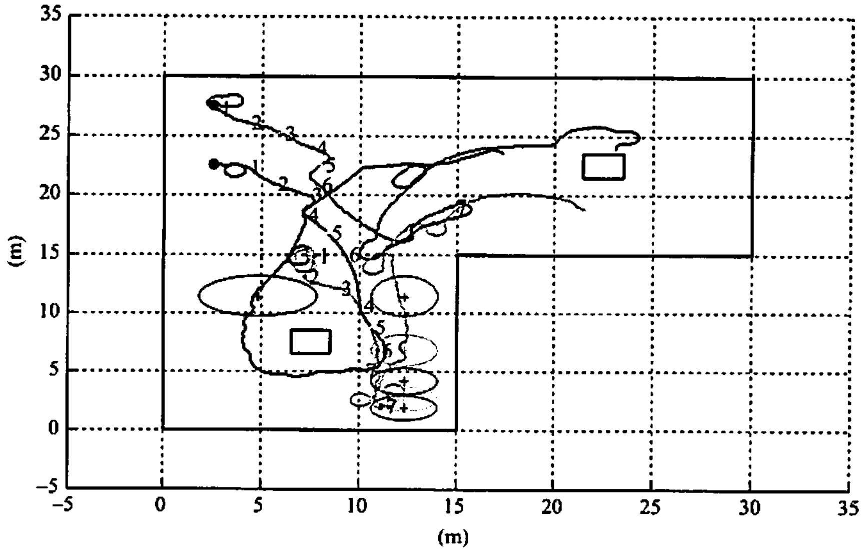
Point	Sentence
1	Move much more forward
2	Move to the right
3	Move more forward
4	Move forward
5	Move a little more forward
6	Move very little more forward

Figure 5 Trajectories performed in experiment 2



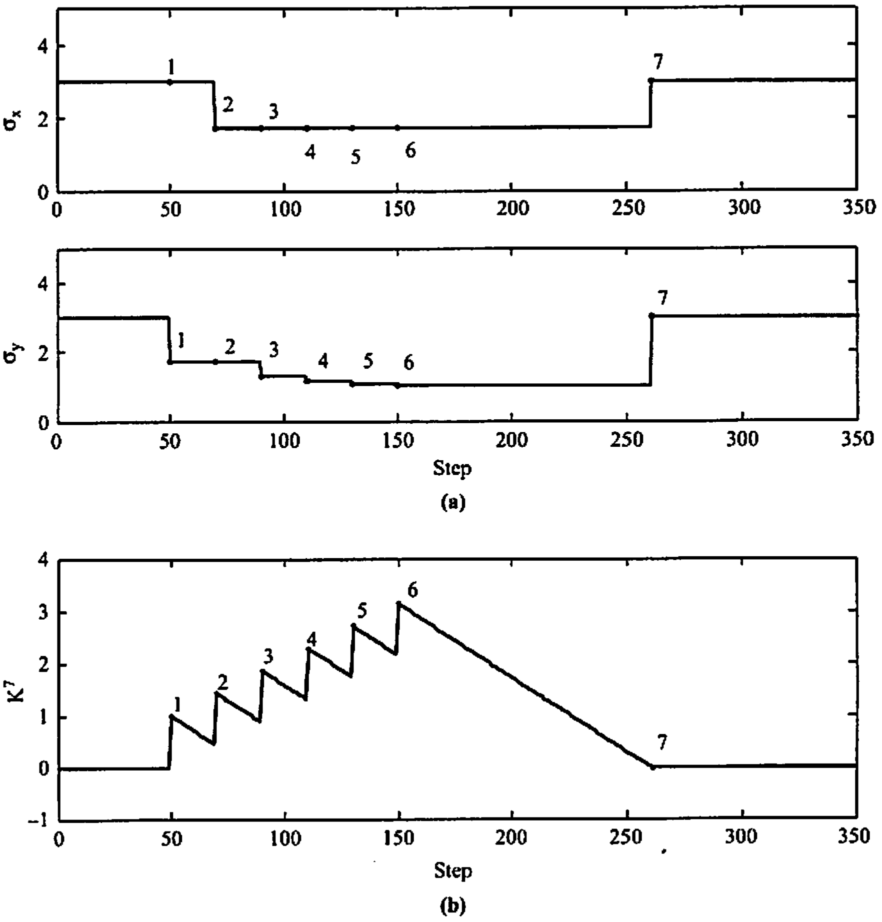
Note: The operator maintains the interest in the same area by issuing repeatedly commands

Figure 6 Trajectories followed by each one of the robots when the interest point is changed



Note: In this case, the operator moves the target point downwards

Figure 7



(a)

(b)

Figure 8 Image of the robots in an exploration experiment

decreased in other case. In Figure 8, an image of the real environment is shown.

Figure 7(a) shows the standard deviation (m) associated to the target point. Note the change in σ_y, when the operator moves the interest point downwards. Figure 7(b) shows the value associated to the weight k_7 at each time step.

6. Conclusions

In this work, a collaborative teleoperation system including human-robot interaction by means of natural language has been presented. The capabilities of this system have been shown with an example of collaborative exploration problem with a team of robots using a behaviour-based approach (Figure 8). The commands issued by the human operator are evaluated and the robots perform their movements taking into account these suggestions. This way, the map is created by taking advantage both from the experience of the operator and taking into account the requirements of the SLAM algorithm. The results of the experiments that have been carried out show the good performance of the system. When the operator proposes new areas of exploration, a change in the trajectories of the robots is caused, with a reinforcement effect when the operator issues new commands repeatedly. This system could be useful in search and rescue operations where the operator can establish a priority in the areas to explore according to his experience.

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