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GARD – AN INTELLIGENT SYSTEM FOR DISTRIBUTED EXPLORATION OF LANDMINE FIELDS SIMULATED BY A TEAM OF KHEPERA ROBOTS

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Abstract. It is absolutely clear that state-of-the-art robots cannot undertake the whole procedure of terrorist bombs neutralization, unexploded ordnances clean up and minefield demining in many environmental situations, such as urban areas, but the main force toward building of a robotic system in these dangerous tasks is to reduce the human presence. The study of robots for demining applications is indeed a scientifically challenging problem that offers wide possibilities of expanding the actual knowledge on several areas of robotics, ranging from localization devices to visual guidance systems, and from navigation on rough terrain to multi-agent co-operation. The ***GPS*** and ***SLAM*** methods are the most efficient tools for a robot localization and mapping. Their extension for a group of mobile robots is of an exceptional importance for the successful creation of the "landmines map". In this paper a co-operative localization algorithm using three mobile robots equipped with localization capabilities for detecting each other has been simulated and tested. Further, navigation algorithms for a colony of mobile robots are proposed. Results demonstrate the localization algorithm applicability, where with a low precision and restricted range, the odometry errors, which normally present problems for mapping, are severely reduced. The simulations show that under certain conditions, successful localization is only possible if the team of multiple robots collaborate during localization by communication and data transferring.

Keywords: Co-operative localization, *Khepera* robots, exploration strategy, communication, data fusion.

1. Introduction

The task of removing unexploded ordnance, terrorist bombs and landmines by specialists puts personnel at great risk associated with the new technologies used in the sub-munitions. These objects have also been subject to weather and environment conditions that could degrade mines (bombs) and cause detonation at any time. Not only the cost of training personnel in locating or gathering unexploded munitions is an enormous task, but this activity also puts the specialists in great danger [1, 2].

The cost of building a single highly intelligent robots fully equipped with complex sensor capabilities is too expensive to use in identification, localization and gathering or neutralization of unexploded ordnance. A single robot can only sense its environment from a single viewpoint, even when it is equipped with a large array of different sensing modalities. A team of robots has distinct advantages over a single one with respect to sensing, because the team of robots can perceive its environment from multiple disparate viewpoints. Each individual robot may not be very capable, but as a team they can still accomplish useful tasks. This results in less expensive robots that are easier to maintain and debug. Team members may exchange sensor information, help each other to scale obstacles, or collaborate to manipulate heavy objects. The key factors affecting the acceptance of small, distributed multiple-robot systems in area clearance are the minimization of failure, the adaptability and reusability [3 - 5]. In comparison to a single large robot system, multiple-robot platforms can drastically shorten the clearance time through distributed parallel execution. Moreover, since each robot is expendable, reliability can be obtained in numbers; that is, if a single small robot fails and all of its capabilities are lost, the team can still continue the task with the remaining robots. The adaptability and reusability of the system are based on the modularity in adding or deleting robots from the group or changing system parameters without affecting the entire system. Even though the simple robotic platform is not as "intelligent" as a single large and expensive system, for mines and bombs identification, a "swarm" of small, inexpensive multiple robots is still capable of achieving the same objective [6]. To account for the advantages of both robot types for the landmine field exploration and demining, a group of autonomous robots for demining, GARD is to be preferred. The GARD can consist of a large number (3-50) of ***reconnaissance robots, RR*** - inexpensive "lowly intelligent" vehicles, together with a number (1-3) of large, "highly intelligent" ***gathering robots, GR***, fully equipped with sensors and gathering manipulator capabilities, all of them controlled by an ***Assisting Operator & Control, AOC*** unit.

This work focuses on the simulation of algorithms for "landmines field exploration" from the ***reconnaissance robots RR*** by using ***Khepera*** robots.

2. Team of Khepera Robots

Several efforts for building small mobile robots have been reported in literature [14]. Although these robots are feats of technological ingenuity, they tend to lack the capabilities necessary for performing tasks going beyond the complexity of follow the leader, move towards a light source, etc. Often a small robot must sacrifice one feature to achieve another. One exception is the ***Khepera*** robot (http://www.k-team.com/) that has achieved both small size and computing complexity. The ***Khepera*** robot is 5 cm in diameter and is capable of significant on-board processing. The robot's base module is equipped with eight infrared sensors for obstacle avoidance. ***Khepera*** robots are modular and support the addition of sensor and processing modules. They are designed to work alone or communicate and act with other robots. The ***Khepera*** robot has a significant feature that allows it to operate in an unknown environment, combine sensor information and act as a central, cohesive unit: ***self-localization***. ***Khepera*** can either rely on a fixed position global sensor (overhead camera) or internal mechanisms (dead-reckoning, IR sensors belt, ultrasonic sensors). The main configuration of ***Khepera*** and some modules are shown in the Figure 1.


a) b) c) d)

Figure 1. The modular *Khepera*: a) base module BM, b) BM and sonar, c) BM, IR belt and CCD line, d) BM, IR belt and TV cam.

By these sensors the robot is capable of identifying objects and building maps of the environment. However, they rely on the presence of a strong light source for orientation and encoders for dead-reckoning. They are also able to communicate via a radio module.

3. Co-Operative Localization

Sensor-based robot localization in an unknown environment has been recognized as one of the fundamental problems in mobile robotics. The problem is frequently divided into two sub-problems: *Position tracking*, which seeks to compensate small dead reckoning errors under the assumption that the initial position is known and *global self-localization*, which addresses the problem of localization with no a priori information [7, 8]. In this case, together with the ***GPS,*** the implementation of ***SLAM – Simultaneous Localization and Mapping***, [9-11], with an appropriate modification for a group of mobile robots, is of an exceptional importance for the successful creation of the "landmines map". The technique has been presented in [12], is modified and simulated for three mobile robots equipped with localization capabilities for detecting each other. The results, obtained with a series of simulation runs, illustrate drastic improvements in localization speed and accuracy when compared to conventional single-robot localization. Further experiments are demonstrated in the paper [14].

3.1. Relative positioning using three co-operating robots

The algorithm for on-line co-operative localization of robots (identification of positions and orientations) during the trajectory execution is based on the scheme presented in [12], extended here for the mobile robots group, consisting of **three robots** - a ***'Parent-robot'*** **LR** and two ***'child-robots'*** **WR** and **BR**, where each robot also acts as a movable landmark to the others. The algorithm is implemented as a set of successive steps for each robot. The trajectories for **LR, BR** and **WR** are supposed to be a priori given as a number of fixed 'start' and 'sub-goal' points. The robot position is described with a triplet consisting of the Cartesian coordinates **(x, y)** of the robot position and its angle of orientation **ϕ**. The trajectories might be given by a human operator or be obtained by different algorithms for a tactical navigation. It is supposed that each robot is equipped with an appropriate controller, so between 'sub-goals' a local path following control is performed. The robot **LR** could be equipped with a camera sensor for reasonably measuring the relative angle of the **BR's** beacon disposition by locating the lamp's horizontal angle β_1. The camera on **WR** could be used to track the **BR**'s beacon and in this way a measurement of the angle β_2 is obtained (see Figure 2.).

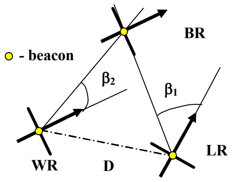

Figure 2. Parameters of the mutual disposition.

The co-operative localization algorithm assumes that a right location of, at least two, of the all three robots, **WR, LR** and **BR** are known and they are considered as the 'start' points, for example **(x_{W0}, y_{W0}, ϕ_{W0}), (x_{L0}, y_{L0}, ϕ_{L0}).** Usually these 'start' points are given by a human operator. The initial topological placement of the robots has to comply with the requirements:
a) The three robots must be placed on the vertexes of the triangle with sides nearly to D, not along a straight line; b) The distances between the 'start' points of robots and 'goal' point have to be considerably longer than the distance D; c) The 'goal' point **(x_G, y_G, ϕ_G)** is known**.** d) A circle of accessibility surrounding the 'goal' point is defined, thus the navigation task is executed if at least one of the three robots reaches to the 'goal' point or crosses the circle of accessibility. The steps of the co-operative localization algorithm are as follows:
Step 1 – The robot's 'start' points with the goal point G are **(x_{W0}, y_{W0},ϕ_{W0}), (x_{L0}, y_{L0},ϕ_{L0}), (x_G, y_G, ϕ_G)**.
Step 2 – The robots **LR** and **WR**, using the cameras, measure the angle $\beta_{L0,0}$ and $\beta_{W0,0}$, pass this information to **BR** using radio link.
Step 3 – **BR** turns its camera against **LR** and measures the angle $\beta_{B0,0}$.
Step 4 – With the three angles $\beta_{L0,0}$, $\beta_{W0,0}$, $\beta_{B0,0}$ and the coordinates **(x_{W0}, y_{W0},ϕ_{W0}), (x_{L0}, y_{L0},ϕ_{L0}), BR** calculates its own actual location **(x_{B0}, y_{B0},ϕ_{B0})** for i=0 by using of the following formulas:

$$x_{B_0} = \frac{1}{\tan\theta_{L_0} - \tan\theta_{W_0}}(x_{L_0}\tan\theta_{L_0} + x_{W_0}\tan\theta_{W_0} + (y_{W_0} - y_{L_0}));$$

$$y_{B_0} = \frac{1}{\tan\theta_{L_0} - \tan\theta_{W_0}}((x_{W_0} - x_{L_0})\tan\theta_{W_0}\tan\theta_{L_0} - y_{L_0}\tan\theta_{W_0} + y_{W_0}\tan\theta_{L_0});$$

$$\theta_{L_0} = \phi_{L_0} + \beta_{L_{0,0}}; \qquad \theta_{W_0} = \phi_{W_0} + \beta_{W_{0,0}}; \tag{1}$$

The angel $\beta_{B0,0}$ is used to determine the value of orientation angle $\phi_{B\,0}$ as follow:

$$\text{if}\,(\pi \rangle \theta_{L_0} \rangle \pi/2) \quad \phi_{B_0} = \pi - \beta_{B_{0,0}} - \theta_{L_0};\ \text{if}\,(0 \langle \theta_{L_0} \langle \pi/2) \quad \phi_{B_0} = \pi - \beta_{B_{0,0}} + \theta_{L_0};$$
$$\text{if}\,(0 \rangle \theta_{L_0} \rangle -\pi/2) \quad \phi_{B_0} = \pi - \beta_{B_{0,0}} + \theta_{L_0};\ \text{if}\,(-\pi \langle \theta_{L_0} \langle -\pi/2) \quad \phi_{B_0} = \pi - \beta_{B_{0,0}} - \theta_{L_0}; \tag{2}$$
$$\text{if}\,(\theta_{L_0} = \pi/2) \quad \phi_{B_0} = \pi/2 - \beta_{B_{0,0}}; \quad \text{if}\,(\theta_{L_0} = -\pi/2) \quad \phi_{B_0} = \pi/2 - \beta_{B_{0,0}};$$

With the coordinates **(x_{B0},y_{B0},ϕ_{B0}),** already identified and shown in Figure 3., the ***'child-robot'*** **BR** is localized.
The movement of the robots towards the 'goal' point **(x_G, y_G, ϕ_G)** is in accordance with the exploration tactic, but the co-operative localization scheme is repeated immediately if any of the robots moves and stops for any reason - tactic step execution, obstacle or landmine identification.

4. Local navigation Strategy for Environment Exploration

For detecting landmines in an environment, it is necessary, that the complete environment is explored in order to find all landmines in the area. Therefore, the exploration strategy has to assure that the complete area is explored and at the same time it has to consider failures or break downs of single robots. The dynamic adaptation of the exploration to the number of robots makes planning strategies and the computation of trajectories

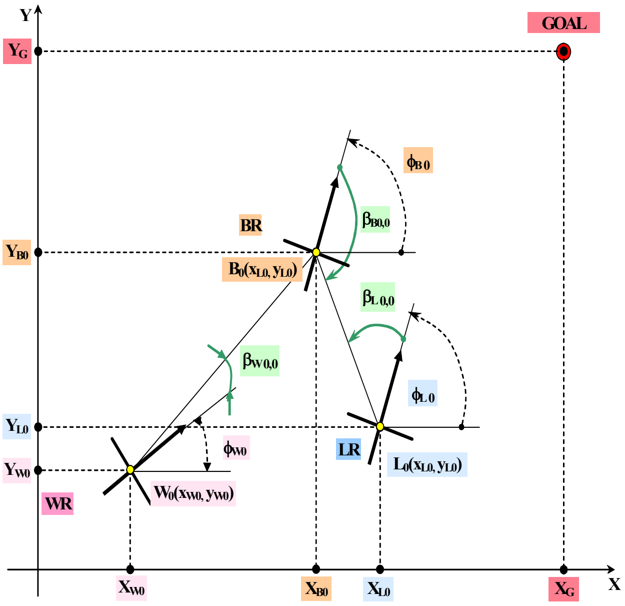

Figure 3. The co-operative localization of the third robot **BR.**

inefficient and difficult to realize. Furthermore, the usage of a master, who is doing the centralized planning, is not preferable, since the failure of the master robot would result in a failure of the whole robot colony. Also, the environment to be explored is usually unknown, with only the limitation of the area given. Unexpected obstacles would in this case present problems to a global exploration strategy.

Here, we describe a local exploration strategy, where each robot computes only the next step for moving dependent on the area around the robot and the position of the other robots. The only requirement for this strategy is a precise positioning system and a global communication system among the robots. With the communication system the robots permanently exchange their current positions, so that each robot knows, which areas of the environment have already been explored and analyzed for possible landmines and which areas require exploration. The exploration strategy works as follows: the complete environment is divided into small quadratic patches, which the robots can easily analyze for possible landmines. The robots can move between the patches also in diagonal direction. After the robots have analyzed their patches, each robot determines the number of non analyzed or free patches around its current position. The results are distributed among the robots and the robot with the smallest number of free patches around firstly determines its next movement. The robot with the second smallest number of free patches around then moves and so forth. For the computation of the next movement an algorithm is used, that determines for each free patch around the robot the costs for reaching it. The cost function C for patch p is given as

$$C\,(p) = N\,(p) \tag{5}$$

where $N\,(p)$ is a function, that computes the number of free neighboring patches around patch p. A visualization of the evaluation is given in Figure 5. After evaluating the costs for all free patches around the robot, it moves to the patch with the lowest costs. That means, the robot goes to that patch, which has the lowest number of free neighbors and which is therefore most unlikely to reach again in the future. What has not been accounted for with that method is the presence of the other robots. They are also able to move to the patch with the least number of free neighbors and therefore increase the likelihood of reaching it. The influence of the robots can be considered with an adapted cost function:

$$C\,(p) = N\,(p) + \alpha * R\,(p) \tag{6}$$

Here, the function $R\,(p)$ determines the number of neighboring robots around patch p and α weights the influence of the neighboring robots. With the cost function in equation (6) the exploration of an area of arbitrary size with an arbitrary number of robots can now be simulated.

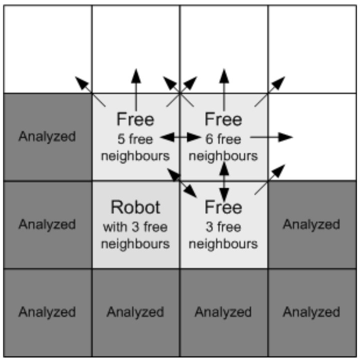

Figure 5. The algorithm determines for each free patch around the robot the costs for reaching it.

5. Experimental Results

The described algorithm for co-operative localization and the technique for local navigation of the robot's group were programmed and simulated under MatLab 6.1. Some simulation results are shown in the Figure 6.

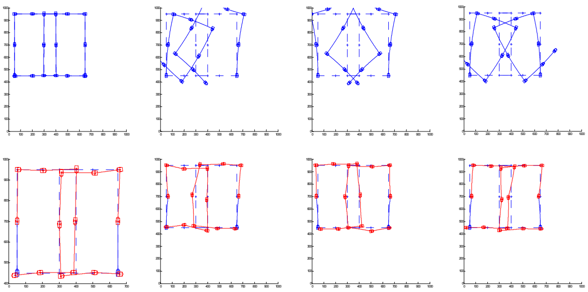

Figure 6. The simulation results with (bottom) and without (top) the co-operative localization algorithm.

They demonstrate the co-operative localization algorithm applicability, where with a low precision and restricted scanning range of the sonar for example, the odometry errors, which normally present problems for mapping, are severely reduced. The experimental setup for "landmine field" exploration with ***Khepera*** robots could look as shown in Figure 7.

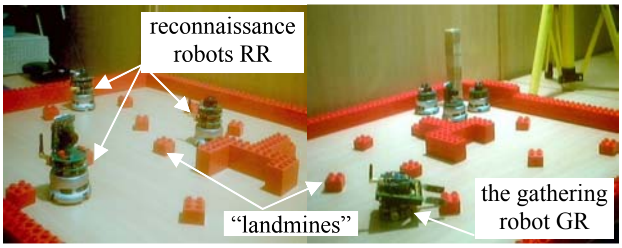

Figure 7. An exemplary experimental setup for "landmine" field exploration with the GARD ***Khepera*** robots.

There were simulated situations with different starting configurations of the robot group. The presented results confirm the algorithm's ability. For a better visualization of the results of the local navigation strategy and a better understanding, a robot stops if it is trapped e.g. all neighboring patches have been analyzed already. In an extension of the algorithm the trapped robots could analyze not only the directly neighboring fields but also the ones the next distance around, but for the results shown here, this extension is not implemented. For several simulated configurations and with $\alpha \leq 2$ the described algorithm always leads to results, where 100% of the area was finally covered. However, the performance largely depends on the shape of the environment and the number of robots used. If the number of robots is too large or the ratio between width and height of the area is very unbalanced, the performance of the algorithm decreases. Also α plays an important role, which can be seen in Figure 7 for an environment of size 15 × 8 and with 4 robots being used.

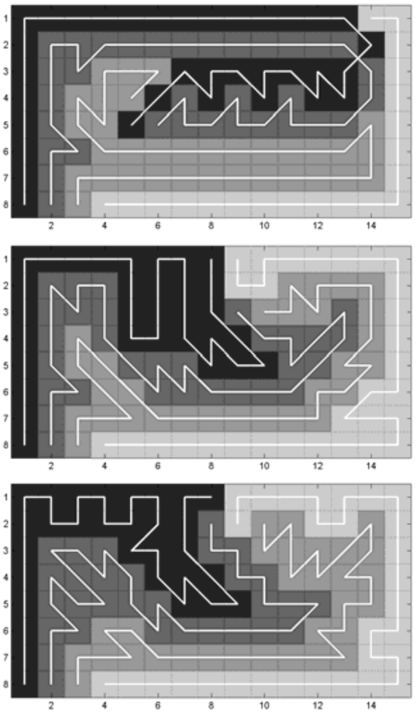

Figure 7. An exploration of environment, size 15 × 8, with 4 robots (top: $\alpha = 0$, middle: $\alpha = 1$, bottom $\alpha = 2$).

The larger it is chosen, the more the robots stay away from each other and if α is set to 0 and robots in the direct neighborhood are not considered at all. Best results were achieved if α was set to 1 or 2. Currently, free patches to the sides of the robot and above and below are weighted equally, leading to optimal results for many configurations within quadratic environments.

6. Conclusion

In this work an algorithm for co-operative on-line localization (identification of positions and orientations) of three robots during the trajectory execution is presented. This algorithm is used further for a local navigation strategy environment exploration. The simulations under MatLab 6.1 confirm the algorithm's ability.

The local navigation algorithm could be improved further by considering the shape of the environment. This means, that the weight ratio between free patches to the sides of the robot and free patches above or below would correspond to the ratio of width and height of the environment.

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