Multi-robotic System with Self-organization for Search of Targets in Covered Area

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Abstract: The paper introduces the multi-robot area coverage problem, wherein a group of robots must inspect every point of a 2-dimensional test environment and surround all contaminations (or enemies) found. Self-organizing robotic systems are able to accomplish complex tasks in a changing environment, using local interactions among individual agents and local environment without an external global control. Our interest in this area is motivated by an involvement in a project with a goal to solve tasks of difficult area coverage and surveillance by a large team of small autonomous robots. In the paper, the architecture to achieve this is described, and simulation results are presented to compare efficiency of coverage of the area and surround of found targets using robots groups having different sensors ranges.

1 INTRODUCTION

Self-organization is one of the most important features observed in social, economic, ecological and biological systems. Self-organizing robotic systems are supposed to be able to accomplish complex tasks in a changing environment through local interactions among individual agents and local environment without an external global control. Developing such self-organizing systems, where desired global behaviours can emerge through local interactions among individuals and with the environment is a challenging task (Meng, 2011).

Team of robots could help to minimize hazardous work for humans. Efficient search and cooperative completion of the task is possible via sophisticated communication methods. A swarm of small mobile robots is a set of inexpensive robots that explore a dangerous environment with aim to locate enemies or other targets. In non-communicative swarming, the swarm comprises homogeneous and anonymous robots, i.e. robots able to recognize other robots but un-capable to identify them individually.

Communicative swarming is distinctively more efficient than non-communicative one as it increases the swarm control ability. In communicative swarming, the swarm robots interchange information concerning their environment, which enables to arrive to information-aware conclusions. Moreover, the robots make use of the information received from each other, which enables to control cooperative behaviors as e.g. cooperative area coverage or cooperative search / exploration. Multi-robot systems communication can be direct or indirect. Indirect interaction uses passive or active mechanism of indirect coordination between agents or actions (stigmergy).

A swarm is defined as a massive collection that moves with no group organization, much like a swarm of bees or a flock of birds. Similar is a formation, the distinction is made in that it maintains a global structure, like a flock of geese or a marching band (http://roboti.cs.siue.edu). Robot formations have been applied to applications such as automated traffic cones, while swarm behavior control has been applied to urban search-and-rescue robotics.

The majority of existing multi-robot systems for pattern formation rely on a predefined pattern, which is impractical for dynamic environments where the pattern to be formed should be able to change as the environment changes. In addition, adaptation to environmental changes should be realized based only on local perception of the robots. In (Jin, Guo and Meng, 2012), a hierarchical gene regulatory network for adaptive multi-robot pattern generation and formation in changing environments is

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proposed.

The traditional artificial intelligence approach to robot control is known as deliberative control. In the sense-plan-act paradigm, the robot senses its environment and, taking into account a model of that environment, decides to start the appropriate action. The weak point of the deliberative control is possible failure in case of unexpected change of the environment. Reactive control does not need a model of the environment or traditional planning, as it relies on a number of simple behaviors.

In the scope of bio-inspired soft robotics behavior is orchestrated rather than controlled (Pfeifer, Lungarella and Iida, 2010). Different bio-inspired multi-robot coordination systems have been developed (http://wyss.harvard.edu): distributed robots for search and rescue, environmental monitoring by highly agile autonomous robots, etc. Agent-based models consist of dynamically interacting, rule-based agents (en.wikipedia.org/wiki/Agent-based_model).

Area coverage is one of the emerging problems in multi-robot coordination (Fazli, 2010). In this task a team of robots is cooperatively trying to observe or sweep an entire area, possibly containing obstacles, with their sensors or actuators. In barrier coverage robot guards are deployed to prevent intrusion (Kloder, 2008).

The foundations of automata theory in swarm systems come predominantly from the cellular robotics systems.

Cellular automata (CA) are abstract models of complex natural systems having large quantities of identical, locally interacting simple components. Modeling based on CA leads to extremely simple models of complex systems. It carries discrete lattice of cells, generally in more dimensions, where each cell in the lattice contains a number of cells. Each cell can interact with the cells located in its neighborhood. Though the CA's construction is simple, its behavior can be very complex. CA modeling is a young domain of Computer Science, where the investigations proceed in two intersecting forms: theoretical study of CA-models as dynamical systems, and development of methods and tools for computer simulation using CA-models (http://ssd.sscc.ru/en/projects).

A cellular automaton consists of a chain (1-dimensional) or lattice (2-or-3-dimensional) of computational cells, each cell being in one of a given set of states that evolve through discrete time steps. The dynamic behavior of the automaton is determined by a set of rules that govern the change of state of an individual cell with respect to its neighbors.

One of practical implications that need to be considered is increasing risk of collisions when two robots attempt to move to the same unoccupied grid cell.

The paper introduces a multi-robot area coverage problem, wherein a group of robots must inspect every point of a 2-dimensional test environment and surround all targets found. Fig. 1 illustrates start positions of robots and positions of searched targets (contaminations or enemies) in the test area.

Similar methods making use of cellular automata do only area coverage or only move on patrol around a given target, e.g. a building. Other methods enabling search for target and its encircling, such as morphogenetic swarm robotic systems (Meng, 2011) use ingenious estimation of shapes and resulting formation of appropriate encircling robots patterns.

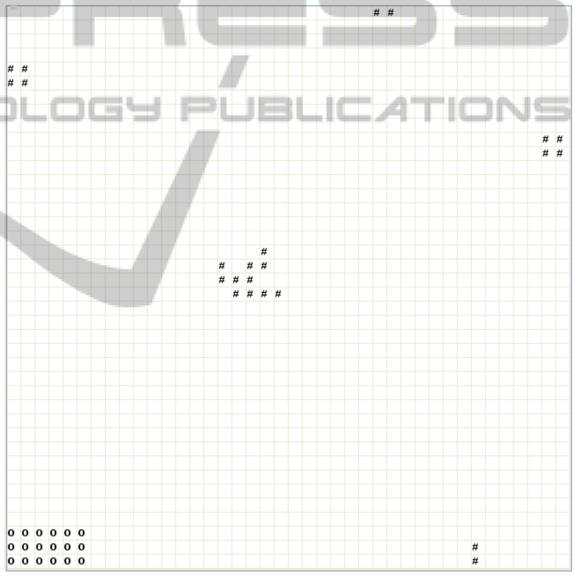


Figure 1: Start position of robots (circles) and searched targets (#) in covered area.

2 COLLECTIVE EMERGENT BEHAVIOURS

Emergence and its accompanying phenomena are a widespread process in nature (Jin and Meng, 2012). Despite of its prominence, there is no agreement in the sciences about the concept and how to define or measure emergence.

The behaviour-based approach (Banzhaf, 2012) has become very popular to cope with several robotic applications, also including service robotics. It refers to direct coupling of perception to action as a specific technique which provides time-bound responses to robots moving in dynamic, unstructured and partially unknown environments.

The behaviour is defined to be a control law for achieving and/or maintaining a particular goal. Usually, robot agents have multiple goals. This requires robot agents to be equipped with a number of behaviours.

A behaviour-based approach assumes a robot to be situated in, and surrounded by, its environment. This means that a robot interacts with the world on its own, without any human intervention, i.e. its perspective is different from that of the observer.

The distinction between collective and cooperative behaviour is made on the basis of communication. Cooperation is a form of interaction based on some form of communication.

The first, essential step enabling the emergence of a collective behaviour is a careful design of the behaviours that any individual robot agent will contain. Further, one has to specify which tasks a group of individual robots can accomplish. Last but not least, a mechanism to initialize the cooperative behaviour, eventually considering the level of cooperative strategies the robots must follow to collectively solve given tasks, is necessary. The result of the actions provided by the individual agents, whose activities must be coordinated to cooperate and solve the global task, will be emergence of a collective behaviour.

A large number of simple robots with limited computational and communication capabilities can be joined to form a multi-robot system (MRS). Robots in an MRS can together fulfil difficult tasks surpassing the capability of a single robot. As they can be made robust, adaptable and still low cost, there have been a large number of successful applications, such as cooperative localization and mapping, collaborative search and rescue, collective construction, etc.

Rescue robots are useful for rescuing jobs in situations that are hazardous for human rescuers (http://emdad1.20m.com). They can enter into gaps and move through small holes, which is impossible for humans and even trained dogs. Robots should explore in collapsed structure, extract the map, search for victims and report the location of victims in map and way that rescue team can reach them. The main task of rescue robots is to acquire information about damaged area and victims (Akiyama, Shimora, Takeuchi and Noda, 2010). Getting the reliable information is given the first priority in rescue activity for disaster mitigation.

An additional potential application of the proposed model is for cordoning off hazardous materials.

In order to traverse through a complex environment, swarm robotic systems need to self-organize themselves to form different yet suitable shapes dynamically, to adapt to unknown environments (D'Angelo, 2007). Insects are particularly good at cooperatively solving multiple complex tasks. For example, foraging for food far away from the nest can be solved through relatively simple behaviours in combination with communication through pheromones. As task complexity increases, however, it may become difficult to determine the proper simple rules which yield the desired emergent cooperative behaviour, or to know if any such rules exist at all.

3 PROBLEM FORMULATION

A large range of research has been done by imitating ideas from nature for designing control algorithms for multi-robot system.

Multi-robot shape construction and pattern formation, a typical task for MRSs, has been widely studied. Algorithms in this research field can be roughly divided into three groups: leader/neighbour-following algorithms, potential field algorithms, and nature-inspired algorithms.

Leader/neighbour-following algorithms require that individual robots follow neighbours or leader that knows the aim or target to which the team needs to go. These following robots should get behind a leader's root in a specific geometric relationship with the ones they follow. The second group of multi-robot shape construction algorithms is based on potential field method. The basic idea of this group of algorithms is that each robot moves under the governance of the gradients of potential fields, which are the sum of virtual attractive and repulsive forces. The third group is represented by nature-inspired algorithms.

The problem we are addressing is to entrap stationary (in future also mobile) targets using a few mobile robots, i.e. coordination mechanisms for the distributed contamination boundary coverage problem with a swarm of miniature robots. In the proposed model, field vector-based area coverage is used in combination with search and surround of some targets distributed in the area. Basic simple behaviours of the robots are:

- area coverage
- collision avoidance
- search for a target

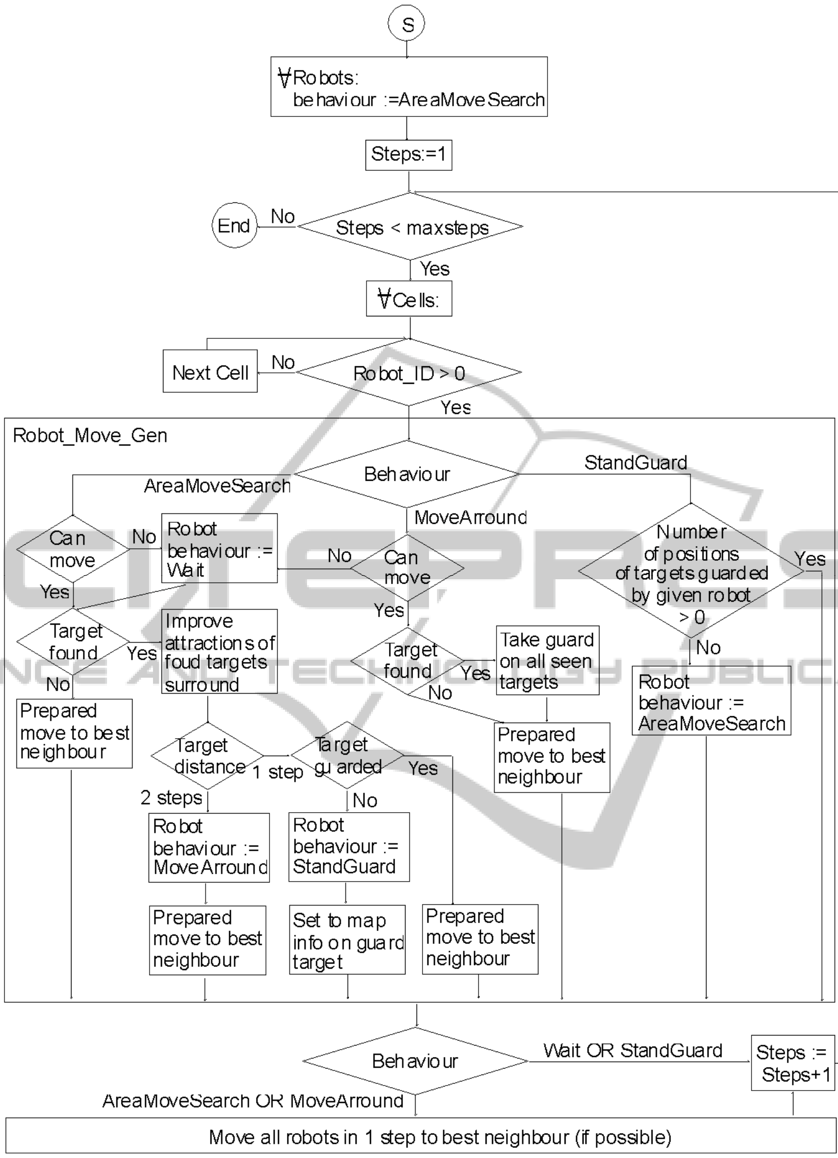


Figure 2: Basic computation flowchart of robot moves based on behaviours.

- walk around the target found
- standing on guard at the found targets.

Fig. 2 shows basic simulation steps (on informational level).

3.1 Assumptions

The following assumptions have been made (Sebestyénová and Kurdel, 2013):

1) All robots move with equal speed.
2) There is a base station containing a sufficient number of robots.
3) All robots have a limited sensing range.
4) The communication range between robots is limited. Robots can communicate information such as targets' location with their immediate neighbours (distance between the two robots is within the communication range).
5) Communication between the robots and the base station is not limited. This assumption will take place but in future, as the model presented in this paper runs only in computer simulation.
6) The robot should distinguish between obstacle and boundary.

3.2 Model and Basic Rules

One way to simulate a 2D cellular automaton (k = 2) is with an infinite sheet of graph paper along with a set of rules for the cells to follow. Each square is called a “cell” and each cell has several possible states. There are several possible lattices and neighbourhood structures for 2D cellular automata. This paper considers square lattices. At start, the robots are arranged in one of the corners of the area (lower left corner on Fig.1). Number of robots and number of rows in which the robots are ordered are selectable. All robots are oriented to Nord at start, and speed of robots equal. From two most common 2-D CA neighbourhood templates (Moore neighbourhood and von Neumann neighbourhood – can be extended) Moore neighbourhood (eight surrounding cells, n = 8) is used in the model. State of a cell is from a set: empty, robot is in it, target is in it.

Neighbourhood size in the model as well as sensors range (e.g. for contamination detection) is two cells distance (r = 2). The model can be further generalized by increasing the possible neighbourhood size to more than two cells distance and by enabling different sensors ranges for different kinds of sensors. For all cells, attractions at start are equal and changes are computed according to robots moves and targets found.

Extra states are used to code the robot's current direction, as well as for remembering cells where some robot already appeared, which is then used for slow forgetting of the robots position history (Sebestyénová and Kurdel, 2014). All cells remember whether and when any of the robots visited the cell. State transition is fired by a set of rules.

Each robot looks at the attractions of the nearby cells and its own direction and then applies the transition rule, specified in advance, to decide its move in the next clock-tick. All the cells change at the same time. Each robot moves to empty neighbour cell with maximal attraction. It tries to move in direction in which it is facing. If this is not possible, the robot direction is rotated clockwise.

Some delicate configuration requiring good decision may on certain occasions happen, e.g. the robot must decide if it is more convenient, or even possible (e.g. sliding along a wall), to turn around the obstacle, instead of passing through, and which direction to select for this turnaround. Walls have been considered as particular kinds of obstacles, too. A serious problem may arise if both of two opposite directions are blocked due to some difficult configuration. In this case the robot does not move for a while, waiting the other robot’s move.

Basic rule for robots moves is specified as

$$a_r^t \times l_r^t \rightarrow c_r^t \quad (1)$$

where a is attraction, l is location of robot, c is cell to which the robot will move, t is time, and r is range. All used data are specified and/or evaluated in subsequent simulation steps in multidimensional cells representing the area (area width × area length × number of used data types, in our case 40×40×8):

- *Attraction* field - at start, attractions of cells are equal (specified maximal attraction value).
- Contamination positions (*targets*) are input data of a simulation tool.
- *Robot* identifiers at positions (start and actual positions) and their directions; number of robots and their starting positions are input data. Robot speed is 1 cell per 1 simulation step.
- Cell occupied by any of robots is an obstacle; no other robot can take the place.
- Just released cell will set zero attraction.
- *Forgetting* a visit of a robot - in subsequent simulation steps cell forgets the visit (in each step a small value, and after many steps cell forgets the visit completely). Using these values, the attraction of the cell again raises.
- Obstacles in area (now only area boundaries are considered)
- Positions of *found targets*
- *Guarded targets* as well as positions and IDs of *robots guarding* on them.
- If the robot views the target (or senses the target according to used sensor), it needs information whether this target is already guarded on by any other robot:
  If not, the robot remains to stay (it starts to guard on and raises the attraction of the target cell and its outskirts).
  If yes, robot continues in walking around the target (one target may cover more cells).
- One robot can guard on more than one target cells according to its sensors ranges.
- The robots guarding on found target cells not only need to see the target, they also need to see each other to form a secure surround.
- *Repulsion* - the robot starting to guard increases the repulsion of its position’s cell.

4 SIMULATION RESULTS

Targets are static objects in the environment that need to be encircled by robots. Robot standing on guard refers to the robot that detects at least one target in the environment. Searching robot refers to the robot not having detected any target in the environment, therefore doing area coverage. Searching robot can become robot standing on guard if it detects a target not yet guarded by any other robot.

Fig. 3 depicts positions of robots after several simulation steps using pseudo-colour plots (starting positions of robots is presented in Section 1 in Fig. 1):

a) in step 25, robot with identifier 9 stands on guard at 3 target cells found in these few steps in the centre of covered area;

b) in step 27, robot with ID 8 takes guard on two target cells previously guarded by robot with ID 9;

c) robots with ID 5, 7, 8, 9 and 10 start guard on some target cells (in step 70);

d) final surround of the target cells in the centre of area covered by 4 robots with ID 5, 7, 10 and 11 (in step 80).

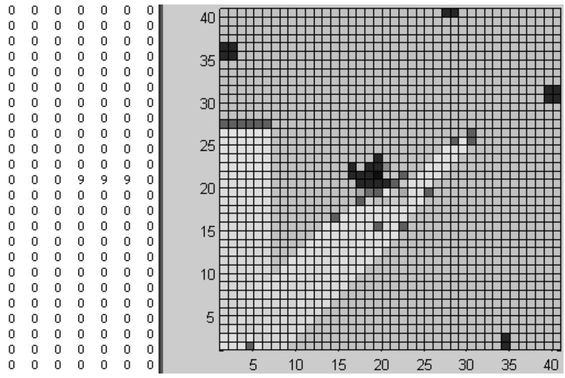
The series of individual figures illustrates changes in attraction field: cells visited by any of the robots exhibit decreased attraction, whereas cells in close vicinity of the found targets acquire increased attraction.

Movement behaviour of robots not detecting any target is governed by the area coverage, avoid collision, and search for target behaviours.

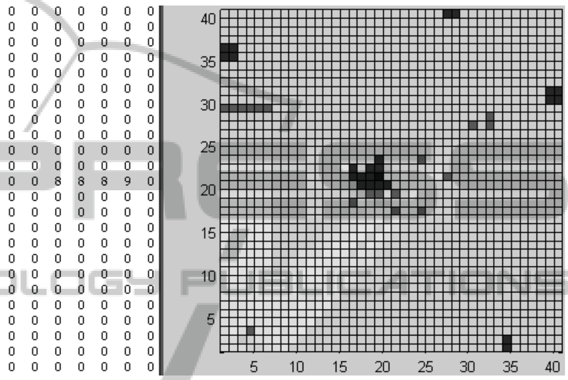
One major advantage of here presented approach, compared to existing multi-robot pattern formation algorithms is that it provides an adaptive mechanism being able to dynamically generate an appropriate surround pattern adapted to environmental changes. Most existing MRSs for pattern formation rely on a predefined pattern, which is not applicable to changing environments.

Entrapping multiple targets is closely related to multi-robot target tracking, where multiple robots are used to track the positions of single or multiple targets. Algorithms for multi-robot target tracking can be divided into two groups. The first group is the region-based approach, in which the robots cooperate to cover a certain region. This way, all the targets in the whole region can be detected and tracked. The advantage of this type of algorithm is that the robots do not need to know the target distribution information. One implicit assumption here is that there is always a sufficient number of robots available to cover the whole region.

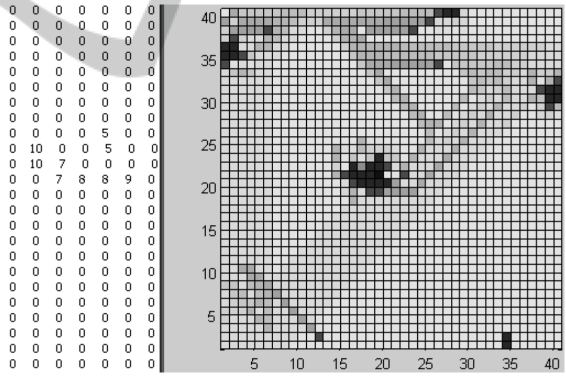
The second group of multi-robot target tracking algorithms is the target-oriented approach. In contrast to region-based algorithm used here, the robots will continuously update the number and location of targets (but they do not have to form



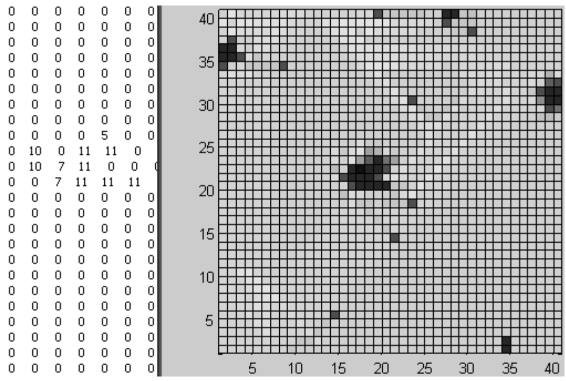
a) in step 25



b) in step 27



c) in step 70



d) in step 80

Figure 3: Position of robots after some steps with ID of exchanging robots guarding on central target.

patterns to entrap the targets). As a result, a large number of targets can be tracked without covering the whole area, which is not acceptable in most of application domains.

The model was made more general with respect to previously published one by implementing the following behaviour: if the robot founds not guarded target, it starts to guard it. If the target found is already guarded by other robot, it will walk around the target. If the target appears to be a contamination, the kind of detected contamination is given by a type of sensors carried by the robot. As the target obviously covers more than one cell, probability to find more cells with not guarded target increases. Each robot can guard more targets in its neighbourhood range (robots sensors range r = 2).

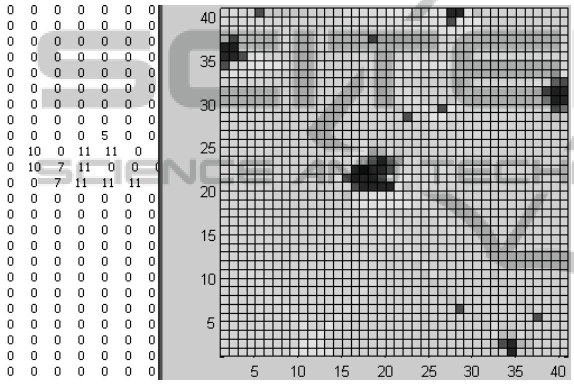


Figure 4: Positions of robots standing on guard around found contaminations in step 94 (6 robots continue in area coverage).

All of the targets in covered area are found and guarded on in step 94. Positions of robots standing on guard around found targets are illustrated in Fig. 4. From the group of 18 robots in the example, 12 robots were enough to guard on all targets in the area, 6 robots continued in area coverage.

For comparison, Fig. 5 illustrates simulation results of the previously presented model, in which the robots sensors range was r = 1 and increase of attractions around found targets was smaller. All targets were found and surrounded in step 280, and only 5 robots could continue in area coverage (to distinguish the cases, the left part of figure is depicted with attraction field changes, right part without them).

5 CONCLUSIONS

This paper introduces the multi-robot area coverage problem, wherein a group of robots must inspect

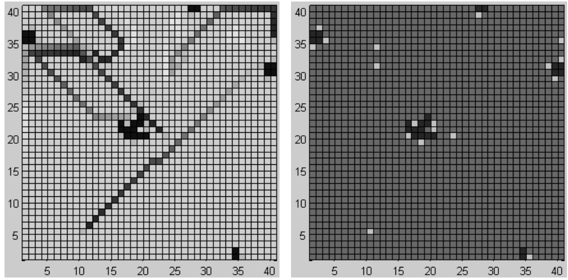


Figure 5: Positions of robots standing on guard around found contaminations in step 280 (5 robots continue in area coverage).

every point of a 2-dimensional test environment and surround all targets found. Although there are many publications on area coverage and there are some - not so many - publications on surrounding of found targets, very little of them combine these two research areas. Similar methods making use of cellular automata do only area coverage or only move on patrol around a given building. Other methods enabling search for target and its encircling use estimation of shapes and resulting formation of appropriate encircling robots patterns. The main new feature of the proposed model compared to existing work is that the target search and surround pattern need not be predefined and is adaptable to environmental changes, e.g., the number and location of the targets to be entrapped. It should be pointed out that successful entrapping of the mobile targets is conditioned on the assumption that the movement speed of the robots is faster than that of the targets. The paper presents new results of the authors compared to their previous work. The main difference in robots behaviours concerns the possibilities arising from longer sensor ranges of robots with respect to the previously published work. Furthermore, robot doing area coverage and search for targets having found the target already guarded by other robot can take over guarding and release the previous robot, which can change its behaviour and continue in area coverage; each robot is now able to guard on more than one target cell; attraction field changes and some other parameters were modified in order to achieve better results. A comparison with previously published work has been made, using the same initial positions of robots and targets. The final goal was this time achieved in smaller number of steps and by smaller number of robots needed for standing on guard. The approach presented here can be generalized in several ways. First, synchronized moves of robots in the group can be replaced by asynchronous ones, so that each robot of the non-homogeneous group will be able to move with its own speed. Likewise, sensor ranges can be made non-uniform. And finally, communication between members of a real mini-robot swarm, as well as with base station can work asynchronously, whenever a new relevant information will be available. In the future, one can investigate in detail the conditions under which the whole system is able to keep encircling the moving targets. The presented model could be used for military applications; another potential application of this model is to cordon off hazardous materials.

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