ATRC: A Swarm-based Robot Team Coordination Protocol for Mine Detection and Unknown Space Discovery

F.De Rango, N.Palmieri
D.E.I.S. Dept, University of Calabria
87036, Arcavacata di Rende (CS)
{derango, npalmieri}@deis.unical.it

Abstract— **In this paper, we consider the problem of exploring an unknown environment with a team of robots to detect and disarm mines. The goal is to minimize the overall exploration time and to disarm all mines in a landscape. We present two approaches for the coordination of robots. An indirect communication, *stigmergy*, inspired to biology is used to help robots to cover the overall area in a minimum time. In this way the robot simultaneously explore different regions of their environment. Moreover, a new coordination protocol called *Ant-based Task and Robot Coordination* (ATRC) is proposed to recruit robots and disarm mines in a minimum amount of time. This approach has been implemented and tested extensively in a simulation environment. The results showed the best convergence time of proposal in term of space discovery in comparison with a well-known algorithm such as the Vertex Ant Walk (VAW). Moreover the effectiveness of proposed protocol is evaluated varying network parameters in the simulation.**

Keywords- **swarm-robotics, swarm-intelligence, ant-based routing, swarm robotics, mine detection, MANET.**

I. INTRODUCTION

The problem of exploring an environment belongs to the fundamental problems in mobile robotics. There are several applications like planetary exploration, reconnaissance, rescue, mowing or cleaning in which the coverage area is one of the robotic mission. [1].

In this paper, we consider the problem of mine detection and disarming performed by a team of mobile robots. The key question during exploration is where to move the robot in order to minimize the time needed to explore completely a certain area.

The use of multiple robots is often suggested to have several advantages over single robot system. In fact, multiple cooperating robots are able to complete many tasks more quickly and reliably than one robot alone and the communication between the robots can multiply their capabilities and effectiveness. Furthermore, using several robots introduce redundancy so there is more fault-tolerance.

The mine detection problem involves the detection and the disarming of randomly placed mines over a field by a finite number of agents with resource constraints. So the problem comprises the sub –tasks such as foraging for mines over the mine field in minimum time, demining the mines through the cooperation of same robots.

In this paper we use techniques of swarm intelligence for coordinating a team of robots to explore the area. Our method is inspired by biology and is based on Ant Colony Optimization. The robot, which have a number of attitudes such as avoiding interference with each other, having sensorial capabilities, sharing the workload by providing information via different sensors or wireless card, having systems that allow the identification and disarming of mines, discover unknown space in an efficient and autonomous manner through the only *stigmergy* and *coordination* to disarm mines through a swarm-based coordination protocol such as proposed in [3-5] from MANET and distributed wireless systems.

The paper is organized as follows. In the next section we present Related work; in Section III we describe our probabilistic approach to coordinate exploration with mobile robots; the new protocol to disarm mine is presented in In Section III; finally simulation results and conclusions are summarized in Section IV and V.

II. RELATED WORK

The problem of exploring unknown environments with mobile robots have been studied intensively in the past. Often this is achieved using the concept of frontiers [3] which are boundaries between explored and unexplored space. Another research proposed central coordination mechanisms [4] [5].

More recently the Hungarian method has been used to solve the robot-to-frontier assignment problem optimally [3].

Many of these types of methods take communication overhead into account (typically in a reactive manner), but few explicity plan to explore beyond communication range limit.

Several other approaches deal with limited communication intentionally, rather than reactively. An early attempt involves maintaining line of sight, in which robots only explore until the threshold of communication is reached [6].

Several authors have proposed " leader-follower" methods, where one robot explored and teammates follow, maintaining connectivity [7] [8].

Another approaches are based to minimize the energy consumed by robots to coverage area [9].

Method from graph theory have been further employed to examine the number of robots required for such a task [10].

Robot teams have also been made to explore unknown environments in “robot packs” using a heuristic that takes communication strength into account to guide their movement [11].

A closely related field of research is that of communication coverage, i.e. arranging robots (or mobile sensor nodes) in such a manner that they are within communication range of the largest possible space. This has been achieved using potential field methods or low level control laws [12] [13]. Also contributions [14-17] performed some task coordination protocols to evaluate the effectiveness of cooperation of more robots in resolving complex problems.

In our approach, which is inspired by Ant Colony Optimization, the robots try to perform two opposite tasks: discover all unknown space and this leads to a distribution of the robots in an area, and, at the same time, after finding a mine during the space discovery, disarming it as soon as possible and this leads the team to concentrate in specific portion of space increasing the unknown area exploration time. In order to perform these tasks robots will sign the crossed cell trough the substance detected by another robots (pheromone); the robots choose the cell that has the lowest quantity of substance to allow the coverage area in less time. However, to recruit robots, we propose not only to use *stigmergy* but also a distributed task coordination protocol.

III. SWARM-BASED METEHEURISTIC FOR SPACE DISCOVERY

In this section we describe the proposal for the robots coordination. Robots need to explore an area in an efficient manner in order to find all mines disseminated on the field. However, when they find a mine they need to be coordinated in order to de-activate that mine.

The area, in which robots can move, is represented by a grid. Moving robots, to support the navigation of the others, leave at any visited point(cell) a constant amount of substance (pheromone). These traces are then used by other robots such as memory of the past visited cells. To make as more realistic as possible the modeling and the diffusion of the substance, we used the concept of the crown. In nature, when we spray a substance the resulting cloud will have a higher concentration towards the center and will tend to decrease moving outside.

This approach allows to gain advantage by *stigmergy* and environment in order to better distribute robots in an-unknown zone reducing the overall discovery time.

In the proposed algorithm robots decide the next movement (next cell) on the basis of heuristic calculations inherited by swarm intelligence and swarm robotics approaches .

The amount of the spray is obtained by the following laws:

$$\Delta\tau_{v,0} = \Delta\tau \cdot e^{-\frac{r}{c_1}} + \frac{\varepsilon}{c_2},\ 0 \le r \le 5,\ 0 \le \varepsilon \le 1\ \ \forall v \in N_r \quad (1)$$

where, N_r is the set of neighbors to the cell where the robot is placed at a distance r ; c_1 and c_2 are constants. For the choice of c_1 and c_2 we consider the case where $r=0$ and $\varepsilon=0$; we obtain that

$$T(0) = \Delta\tau \quad (2)$$

T(0) represents the amount of substance that is sprayed into the cell where the robot is placed (it is the amount of substance present in the center of the crown that has the highest concentration of the substance); so the *T(r)* function will be decreasing as follows:

$$T(0) > T(1) > T(2) > ... > T(5) \quad (3)$$

The second constant in second member of equation $\left(\frac{\varepsilon}{c_2}\right)$ will be $c_2 = 10^{r+3}$. This introduced heuristic computation permits to model the noise in the scent distribution. It has been determined through simulation campaigns.

The constant c_2 can be seen as a factor reducing the value of ε ($\varepsilon \in (0;1)$) modeled as a noise.

Let ρ be the coefficient taking into account the temporal dispersion of the pheromone in cell. For each time unit, ρ is the percentage of substance that evaporates, then (1-ρ) is the substance remained in the cell. For the calculation of ρ is used a coefficient *ERU%* (Evaporation Rate Unit) which regards the evaporation rate per unit of time spent. Indicating the last time in which the cell has been visited with t_V and the current time t, $(t-t_V)$ is the time spent since the last visit of the cell.

Multiplying this time per *ERU* we has the coefficient of total evaporation:

$$\rho = (t - t_v) \cdot ERU_{\%} \quad (4)$$

When a robot moves to a cell that already contains a certain amount of substance $(1-\rho)\cdot\tau$, the amount of substance that results in the cell i where the robot is moving is given by:

$$\tau_i^{n+1} = (1-\rho)\cdot\tau_i^n + \Delta\tau \quad (5)$$

The novel pheromone is indicated with index (n+1) because it represents the $(n+1)$-th change produced on the cell i by the entering robot; $\Delta\tau$ is the amount of the new scent sprayed by the entering robot.

To generalize the case of a spray with a crown with maximum radius r we have to account also the contribution of scent given by other robots moving in the neighbor cells on the basis of the spatial diffusion of the pheromone modeled in (1). For this reason a general formula can arranged as follows:

$$\tau_{i,t}^{n+1} = (1-\rho)\cdot\tau_{i,t}^n + \sum_{v=1}^{|N_r(i)|}\left(\Delta\tau_{v,t}\cdot e^{-\frac{r}{c_1}} + \frac{\varepsilon}{c_2}\right);\ \forall v \in N_r$$

(6)

Each cell contains an initial pheromone value and heuristic value. The robot, at any time instant, is on a particular cell s and it is surrounded by a number of neighbors N=| N (s) |. In this situation the robot makes a decision, based on the characteristics of each available cell.

Therefore it is necessary to evaluate the goodness of a given choice in comparison with another one. To calculate the choice probability of every single available cell (neighbors), it is used the following formula:

$$p\left(c_i|s\right)=\frac{[\tau_i]^{\alpha}\cdot[\eta_i]^{\beta}}{\sum_{i\in N(s)}[\tau_i]^{\alpha}\cdot[\eta_i]^{\beta}},\forall c_i\in N(s) \quad (7)$$

where $p\left(c_i|s\right)$ represents the probability to choice the cell c_i starting from cell s; $N(s)$ is the set of neighbors to the cell s, τ_i represents the amount of pheromone in the cell c_i; η_i is the heuristic information in the c_i; α and β are two parameters which determine the relative influence of pheromone value and heuristic information.

In general $\alpha, \beta \neq 0$, so as to balance the weight to be given to pheromone values and heuristic values of the cell. In the formula the initial values to associate with artificial pheromone τ and the heuristic value η can be chosen in a way to affect the agents behavior.

An agent must obey to certain laws for the selection of the next cell in which to move. In this work, two laws are implemented:

- MAXIMUM_TRACE_FOLLOWER
- MINIMUM_TRACE_FOLLOWER.

In the MAXIMUM_TRACE_FOLLOWER the chosen cell is:

$$\boldsymbol{c_d} = \boldsymbol{c_i} / \boldsymbol{p}\left(\boldsymbol{c_i}|\boldsymbol{s}\right)= \max\left[\boldsymbol{p}\left(\boldsymbol{c_i}|\boldsymbol{s}\right)\right] \ \forall \boldsymbol{c_i} \in \boldsymbol{N}(\boldsymbol{s}) \quad (8)$$

In the MINIMUM_TRACE_FOLLOWER the strategy is:

$$p_{\min}\left(c_i|s\right)=1-p_{\max}\left(c_i|s\right), \ \forall c_i \in N(s) \quad (9)$$

In this case p_{min} takes into account the cells with less pheromone value. To calculate the relative probabilities of the cells in which robot can move, will then use the formula:

$$\boldsymbol{p}\left(\boldsymbol{c_i}|\boldsymbol{s}\right)=\frac{\boldsymbol{p}_{\min}\left(\boldsymbol{c_i}|\boldsymbol{s}\right)}{\sum_{\boldsymbol{i}\in \boldsymbol{N}(\boldsymbol{s})}\boldsymbol{p}_{\min}\left(\boldsymbol{c_i}|\boldsymbol{s}\right)}, \ \forall \boldsymbol{c_i} \in \boldsymbol{N}(\boldsymbol{s}) \quad (10)$$

The robot moves into the cell that satisfies this condition:

$$\boldsymbol{c_d} = \boldsymbol{c_i} / \boldsymbol{p}\left(\boldsymbol{c_i}|\boldsymbol{s}\right)= \min\left[\boldsymbol{p}\left(\boldsymbol{c_i}|\boldsymbol{s}\right)\right], \ \forall \boldsymbol{c_i} \in \boldsymbol{N}(\boldsymbol{s}) \quad (11)$$

In this way the robot will prefer the exploration of the less frequented areas by other robots.

In the coverage area task the implemented law was the *MINIMUM_TRACE_FOLLOWER* to allow the coverage area exploration in a minimum amount of time. Instead, the *MAXIMUM_TRACE_FOLLOWER* is applied to reach the cell where there is a mine to disarm.

The symbols and their meanings used in the previous sections are presented in the table 1.

Simbols	***Meaning***
τi,t	Pheromone value in the cell i at t time
τi,0	Initial pheromone value in cell i
Δτ	Increase of pheromone value in the cell
ηi,t	Heuristic component in the cell i at t time
ηi,0	Inizial Heuristic component in cell i
α	Parameters of pheromone value
β	Parameter of heuristic component
c_1	Decrease factor in exponential distribution
c_2	Decrease disturbance in the diffusion of substance
ε	Disturbance factor in the diffusion
ρ	Evaporation coefficient
$N_r(s)$	Number of neighbor cells to cell *s*
ERU%	Evaporation rate per unit time

Table 1:- Symbols adopted in the problem formulation.

IV. ANT-BASED TASK AND ROBOT COORDINATION (ATRC) PROTOCOL

In an distributed wireless communication system robots can communicate among them by exchanging messages in a multi-hop forwarding. The messages that a robot can send or receive are:

HELLO: Hello packets are used to notify the robot presence in its transmission range to other robots. A HELLO packet, contains the ID of the sending robot. When a robot receives this packet becomes aware of the presence of another robot in its range and it writes the ID in a data structure (neighbors table) which takes account of all the robots in the communication range. If after a time period it does not receive HELLO packets from other robots present in its data structure, it deletes the correspondent entry line. In this way, a robot will know the robots that can be reached directly (one-hop).

Requiring Task Forward Ant (RT-FAnt): it is a packet sent by the robot that detected a mine (coordinator) to know how many robots are available to disarm the mine.

Requiring Task Backward Ant (RT-BAnt): it is a packet that a generic robot (called forager) sends in response to a RT-Fant.

Recruitment Fant (R-FAnt): it is a packet sent by a coordinator, to the link from which came the higher number of Bant responses (RT-Bants) ; this link has higher recruitment probability.

Recruitment Bant (R-BAnt): it is a packet sent by a robot in response to positive recruitment (R-Fant) by a coordinator.

Leaving position (LP): if a R-Bant, generated by a robot in response to the R-FAnt, does not arrive to coordinator within a certain time (it is a recruiting timer), and there is the situation in which more recruited robots than necessary are present on the cell to disarm the mine, recruited robots, not recorded in the coordinator data structure, will receive a message from the coordinator to leave the actual position (LP). All robots receiving this message becomes forager again changing their state.

The behavior of the robots in each state has been described below in the Fig.2 on the basis of the events that occur:

Forager Robot State (FRS): it is the initial state of each robot. In this state the robot searches in the environment for mine detection .

Coordinator State (CS): a robot becomes coordinator when it detects a mine.

Recruiter State (RS): the robot enters in this state when it is recruited as the coordinator for the mine disarmament.

Disarmer State (DS): Once all recruited robots reach their destination, the coordinator sends a packet in which it orders them to become disarmer robots for a defined time (it is regulated by a timer demining time).

Waiting State (WS): a robot recruited by a coordinator, once it reaches its destination, enter into this state and they wait to receive by coordinator the order to become disarmers and change their state.

For the most time, a robot is forager. Its operations are:

Processing packet content: when a robots receives a packet depending on its content it can become a coordinator, or recruiter or it forwards the packet to another destination. After forwarding the packet or in absence of receiving packets, the forager performs its main task to explore new spaces to detect the mines.

Signing Cell: the robot signs the cell in which it is placed by spraying a substance detectable by sensors of the other robots;

Choosing next cell: through the calculations of choice probability described in previous section, the robot selects the cell where it moves. If during the search it detects a mine the robot becomes the coordinator, or if it reaches its destination the process starts again. When a forager finds a mine in a cell and there is no other robot already in this cell, it becomes the coordinator for the disarmament of this mine.

The coordinator perform these operations:

FAnt Generating and Forwarding: it creates and sends a broadcast request in the network: in this step the coordinator sends a RT-FAnt to know how many robots are available for the disarming the mine. The RT-FAnt, identified by the triple (ID-Coordinator, Task-ID, ID-Fant), is sent in broadcast to all robots in the transmission range.

Waiting timer: after sending the RT-FAnt, the coordinator sets a timer; after timing out it controls the number of received RT-Bant. If the coordinator doesn't receive enough replies, analyses the number of received replies: if it doesn't receive any replies it becomes a forager, else it creates and sends a new Request Task FAnt and forwards in broadcast on the network. If the coordinator has enough replies to perform the task, it creates and sends R-FAnt on the link with higher probability of recruitment.

Waiting incoming robots: the coordinator waits for the incoming recruited robots.

Submitting disarming order: When all needed robots are recruited into the interested cell, the coordinator sends a disarming message and it becomes a disarmer too.

When a robot receives a RT-Fant packet and sends a RT-Bant to the coordinator, it becomes a recruiter. Then, its task is to reach the destination cell (where it is present the mine). The recruiter execute this operation:

Checking cell: in this step the recruiter checks if visited cell is the destination cell. If it is in the destination cell becomes waiter and it waits the disarming message by the coordinator otherwise it performs the same operation of forager with the exception of the detection mine task.

Signing cell: the robot signs the cell spraying the perfume that follows the evaporation laws described in the previous section.

Choosing next cell: the recruiter checks the cells in which it could move and chooses the cell which minimizes the distance to the destination (cell where there is the mine). If in the selected cell there is another robot, it takes a probabilistic decision as if it was a forager. After moving towards this cell it begins the decision process again.

A. *Forwarding mechanism of FAnt and BAnt*

In the networks using a routing type Ant usually use probabilistic routing tables. To ensure that every FAnt sent on the reverse path forwarding to the host that generated it, each crossed node enters its ID in the packets [14]. Once it reached its destination a Backward Ant (BAnt) response, where crossed robots and additional information for updating routing tables are copied, is generated and forwarded to coordinator. BAnt generated follows the route tracked by FAnt so reaches the destination host.

During its travelling in the network BAnt updates the entry in the routing table of each crossed node. The law for updating the pheromone is usually based on the degree of the path, that is the number of hosts crossed by FAnt to reach the destination. The routing table in this work are not deterministic, but probabilistic. The packet format of FANT and BANT is presented below.

ID Coordinator	ID Task	Task Type	p_D	τ_0	…

Fig.1 Packet format of FAnt/Bant packet.

ID Coordinator : ID of the coordinator; it is inserted in a RT-FAnt;

Task ID: it is the ID of the task requested by the coordinator. Each time the same coordinator runs different task this value is incremented;

Task Type: in this case there is only one task, but this field can be useful for future purpose and extensions.

ID Coordinator, Task ID and Task Type allows the unique identification of an entry. Initially, when a RT-FAnt is sent on the network, each robot receives RT-FAnt and creates an entry in the routing table and sets a balanced selection probability of the neighbors. These probabilities are then updated through the response RT-BAnt. Each robot that receives an RT-BAnt from a particular link, updates the probability associated to that link and decreases the other link probabilities through the use of two concepts:

Evaporation: it is a rule to decrease the amount of pheromone of the link where ants do not pass. It is applied such expressed in eq.(14).

Reinforcement: it is the rule to increase the most important link on the basis of the ants crossing the paths. It is applied according with eq.(13).

Let p_D be the degree of the path. Usually the degree of the path depends on the number of hosts crossed to reach the destination, but in this case it is considered the distance of the robot that creates the RT-Bant to the destination (cell where the mine needs to be deactivated). The degree of the route is calculated through the coefficient ρ.

$$\rho = \frac{1}{p_D} \tag{12}$$

Longer the distance the recruited robot from coordinator lower the ρ value is . The evaporation is applied to all links, while reinforcement learning is applied to the link receiving the RT-BAnt. The increase follows an exponential law below:

$$g(\rho) = \rho^{\frac{1}{k}} \qquad (13)$$

where k is the intensity constant.

τ is the pheromone value on a particular link, the new pheromone after evaporation is given by:

$$\tau = (1-\rho)\cdot\tau \qquad (14)$$

In this way the probability of the link which receives the highest number of RT-BAnt increases. Having to submit the RT-FAnt in a deterministic way, a robot is able to choose the link with the highest recruitment probability.

If the received R-Bant contains a recruitment task during the travelling for each link, the robot only executes the process of evaporation. This is made to improve the link selection probability, indicating a high number of robots willing to perform the task requested.

B. Task Request BAnt and FAnt Management

When the *coordinator* sends *R-FAnt*, only foragers process this packet. If the packet is received by robots that are in other states (different by foraging state) they forward in broadcast the *FAnt.*

The forager receiving *R-FAnt* performs same operations:

Checking uniqueness of received Fants: a forager, after receiving a packet containing R-FAnt, controls if it processed this packet previously. In this case the robot drops the packets and carries on its operations, otherwise it saves the ID FAnt in a data structure and processes the packet content.

Processing requirements: If the received Fant is not duplicated, the forager checks the required characteristics. If it is able to perform the task, controls the percentage of response *Bant*, relating to the *FAnt*, already forwarded to the coordinator and decides in a probabilistic manner whether to forward or not its answer. Next it creates and sends R-BAnt to the *coordinator*, through the use of the fields " Required Robots" and "Generated Bant" in the *type* field of the packet. The Forager, finally, sends received FAnt in broadcast also if it is not able to perform the task.

C. Recruiting FAnt and BAnt Management

A coordinator, after receiving enough responses by foragers, sends R-FAnt on the link that has the higher success probability. The foragers receiving this FAnt execute these operations:

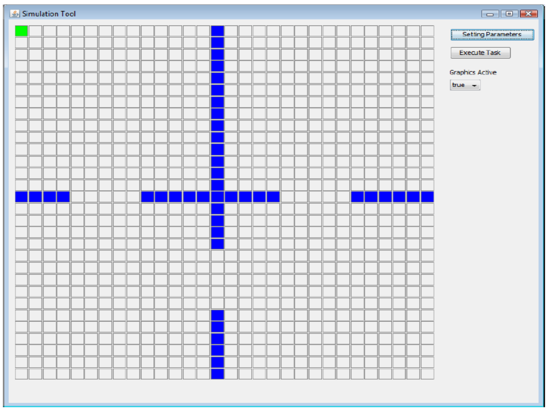
Processing R-FAnt: Initially, the forager checks whether the FAnt has been previously processed; in this case it discards the packet. In other case it adds its identifier in the list of crossed robots by R-FAnt and then processes the requirement request.

BAnt Management: if the robot decides to participate in the disarmament of the mine, it creates and sends a R-BAnt to coordinator as a recruitment confirmation. The R-BAnt updates the routing table of the crossed nodes.

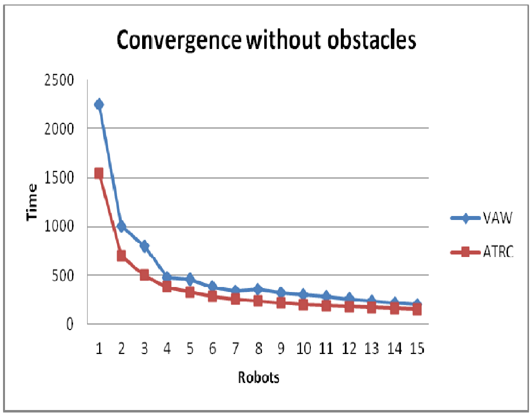
FAnt Forwarding: independently by the response of R-BAnt, a forager receiving a R-FAnt creates and sends new R-FAnt to another robots if there is the need to recruit other robots on the link with higher recruitment probability otherwise, if itself is the last robot, it does not forward any R-Fant.

V. Performance Evaluation

The simulations were executed varying various parameters of the problem. We started to evaluate the Ant-based Team Robot Coordination in comparison with VAW in a area with obstacles and not. We use a minimum of 4 robots (needed number to disarm a mine) until a maximum number of 35, with a transmission range RW=9 that is the optimal value to simulate (for space limitations it is not shown the tuning on the transmission range under different grid size and robot density). In Fig.2 and Fig.3 the completion time under 3 mines randomly distributed in the field and with an increasing number of robots is shown. As we expected, an higher number of robots reduce the cells discovery time for both VAW and ATRC. Our approach is able to obtain lower discovery time through the swarm based solution.



a)



b)

Fig.2: a) VAW vs ATRC in area without obstacles 30x30; b): Map 30x30 divided into four areas.

In Fig.3 the adopted map with obstacles is shown. Obstacles are represented by blue square whereas cells to discover are represented by empty square. The green square on the left high corner is the starting point where the robots team start the field exploration.

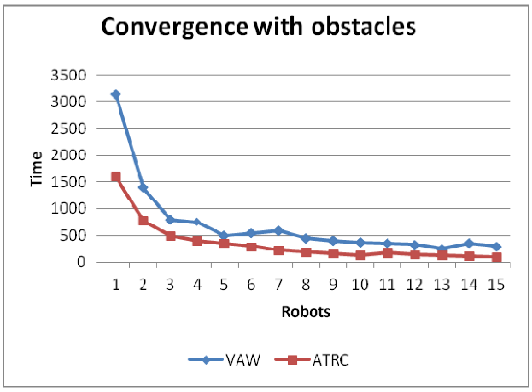
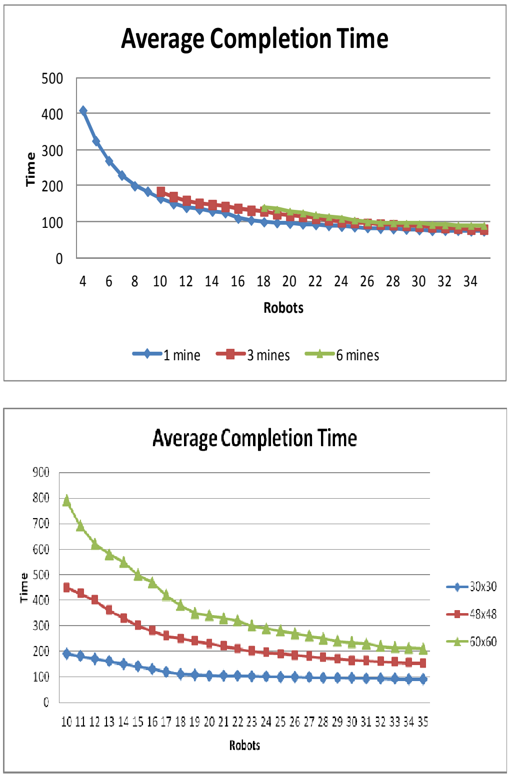


Fig. 3: VAW vs ATRC in area with obstacles 30x30.

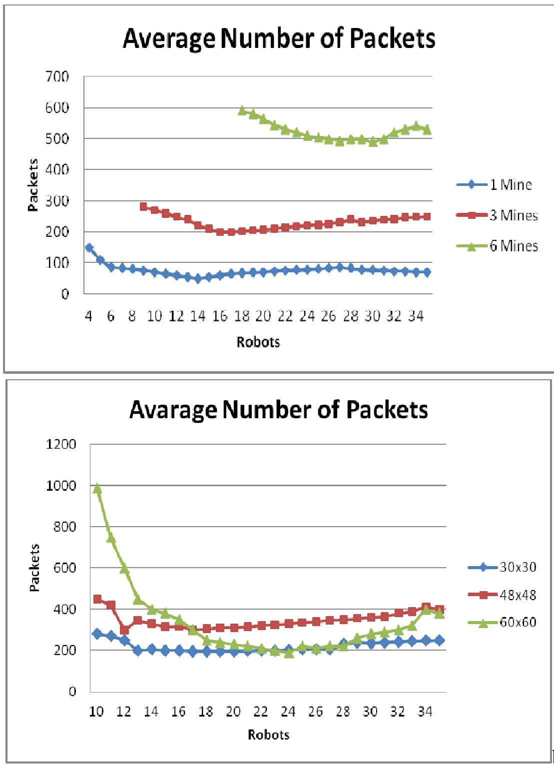
In Fig.4 the average convergence time is shown; it increases for larger unknown area and for an higher number of mines. This is due to the increase in the path length from *coordinator* and *forager* and to the high number of cells to visit. Also in this case an higher number of robots can assure a lower convergence time. However, we do not need to increase a lot the number of robots but we can stop to a minimum number after which no more gain is obtained.



a)

b)

Fig.4. Convergence time vs number of robots in a research area with: a) different number of mines to be disarmed; b) different number grid size and transmission range RW=9.



a)

b)

Fig.5: a) Average number of packets varying the number of mines; b) Average number of packets varying the dimension of area.

Regarding the number of packets sent in the network for coordinating the robots (Fig.5), it mainly depends on the number of mines in the area. The number of robots does not affect the performance because ATRC, such as it has been designed, avoids an excessive increase of packets in the network. In fact the number of packets in the network is nearly constant increasing the number of robots with a certain number of mines; instead increasing the number of mines with a certain number of robots the protocol overhead increases because more robots need to be recruited and contacted. In Fig. 5.b the flows of packets varying the area size are shown. In this case the number of packets increases proportionally to the size of area when there are few robots because the network is instable, but the network reaches the stability increasing the number of robots.

VI. CONCLUSIONS

The formulation of a multiple task problem is proposed: mine detection and unknown space discovery. At this purpose a new protocol able to disseminate a recruiting request and to recall the right number of robots in the minimal amount of time is presented. This protocol applies a probabilistic approach inherited by swarm-robotics in order to offer a scalable and distributed solution to the mine disarming field issue. Such as verified by simulation results, our algorithm reduces the convergence time in comparison with VAW. Moreover, the increase in the number of mines in the field lightly increase the average convergence time while the increase of the research area (cells) lightly affect the system performance. Self-organization of robots team with the addition of wireless communications to disseminate task and coordinate the robots reveal to be a good merging approach in the design of new kind of protocols in this interesting research area.

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