Coordination in a Multi-Robot Surveillance Application using Wireless Sensor Networks

Sahar Trigui*, Anis Koubâa ¶‡, Maissa Ben Jamâa §, Imen Châari * Khaled Al-Shalfan ‖

* CES Research Unit, National School of Engineers of Sfax, University of Sfax, Tunisia.
¶ COINS Research Group, Al-Imam Mohamed bin Saud University, Saudi Arabia.
‡ CISTER Research Unit, Polytechnic Institute of Porto (ISEP/IPP), Portugal.
§ ReDCAD Research Unit, National School of Engineers of Sfax, University of Sfax, Tunisia.
‖ Research Unit of Sciences and Technology, Al-Imam Mohamed bin Saud University, Saudi Arabia.

sahar.trigui@ceslab.org, aska@isep.ipp.pt, mbenj@redcad.org, imen.chaari@rtrackp.com, kshalfan@imamu.edu.sa

***Abstract*—Cooperative robots and their integration with Wireless Sensor Networks (WSNs) is an expanding area that still deserves significant research efforts. This paper presents a multi-robot surveillance application supported by a WSN. We investigate the problem of multi-robot coordination for target tracking and capturing. One key distinction of our problem model is to consider a WSN that supports the mission of the multi-robot team. We devised three mechanisms: centralized, distributed and market-based algorithms, which were extensively evaluated under the Player/Stage simulator. Simulation results show that the centralized approach is the most likely solution able to maintain an efficient system cost.**

I. Introduction

Robots are typically intended to collaborate together to achieve a given goal. In order to maintain the efficiency of the system, there is a crucial need to specify coordination policies that define how tasks are assigned to the robots. Robot coordination can be seen as an instantiation of the Multi-Robot Task Allocation (MRTA) problem. The latter is considered as one of the most typical problems in the robotic field. Several research works [1], [2] have been conducted for answering the following question: Which robot should execute which task? Dias et al. [3] provided a comprehensive survey on multi-robot coordination (based on market-based approach).

In the literature, there are three typical approaches devised for ensuring multi-robot coordination [3], namely: *(i.) the centralized approach*: it assumes the knowledge of global information by a central agent (e.g. control station), which is able to calculate an optimal (or near-optimal) solution to the allocation problem, *(ii.) the distributed approach* [4], [5]: decisions (or local solutions) are based on local information for each agent performing the task (e.g. robot) *(iii.) the market-based approach* [6], [7]: it assumes that solutions are built based on a bidding-auctioning procedure between the working agent (e.g. robot) and a coordinator for allocating tasks for low-cost bidders. In most of these approaches the multi-robot system is assumed to be autonomous [8], [9], [10]. Another alternative for mobile robotic applications consists in taking benefit from the Wireless Sensor Network paradigm as a base for acquiring additional knowledge about the environment. The idea is to feed the robots with the additional information that can be carried out by the WSN infrastructure, which provides substantial support to the robotic system to perform their required actions. This will induce new coordination challenges. The contribution of this paper lies in investigating the coordination strategies between a multi-robot team and a WSN for undertaking the mission of target tracking and capturing in an indoor surveillance application. In fact, robotics and WSNs have mostly been considered as separate research fields and little work has addressed the marriage between these two technologies [11], which argue the added values of this paper. We present three coordination strategies: centralized, distributed, and market-based for solving the robot-sensor coordination problem. Further, we present an extensive simulation study using Player/Stage simulator to evaluate and compare the performance of the proposed strategies.

The remainder of this paper is organized as follows: Section II states the problem of MRTA in the indoor surveillance application, and describes the system model. Section III gives a detailed presentation of the three proposed strategies for multi-robot coordination. Section IV reports the simulations results conducted under Player/Stage simulator. Finally, in Section V we conclude the paper.

II. Problem Statement and System Model

In this paper, we tackle the problem of multi robots coordination in an indoor surveillance application. Coordination defines how robots are cooperating together and which robot should execute which task. In typical multi robot systems, robots are generally assumed to be autonomous where the intelligence, i.e. processing and data analysis, is embedded in the robot. Thus, the cooperative work between mobile robots in a field requires distributed and ah-hoc communications between the different mobile robots, which might increase the solution complexity due to their high mobility. The cooperation becomes even harder if real-time guarantee is a major requirement of the robotic distributed application. Another alternative for mobile robotic applications consists in taking benefit from the Wireless Sensor Network paradigm as a base for acquiring additional knowledge about the environment. The idea is to feed the robots with the additional cyber-physical information that can be carried out by the WSN infrastructure, which provides substantial support to the robotic system to perform their required actions. As an illustration, we investigate in this paper the use of WSN to support the coordination between robots for a surveillance application in which a set of pursuers are intended to capture a set of intruders. The coordination problem can be viewed as a task allocation problem. It can be roughly formulated as follows: *Given a set of n pursuers and a set of m intruders and a sensor network distributed in the environment, how to efficiently allocate tasks to mobile robots to capture the intruder(s) with a minimum cost, using the WSN*. The cost can take several forms such as mission duration, consumed energy, path traveled, etc. The intruder is considered as captured if the distance between the intruder and the robot is less than a certain threshold. The model of our application consists of the following components:

- Homogeneous mobile robots: also referred to as pursuers. They are responsible for following and catching the intruders based on the control commands sent by the central control station or from data provided by the WSN depending on the coordination strategy. Mobile robots are assumed to wirelessly communicate with each other and also with other components.
- A static wireless sensor network: it is deployed in the area of interest in order to maintain collaboration with the robots in accomplishing the whole mission. The sensor nodes are responsible for detecting the intruders, locating mobile robots and supporting their missions.
- A central control station: it represents a data collection center used to remotely monitor and control the area of interest. It typically plays two roles: First, it collects data from the mobile robots and the WSN to get an updated system status (robot locations, sensor events, etc.). Second, it remotely controls and commands the robots based on available information (i.e intruders location) received from the WSN and the coordination strategy.

III. Multi-Robot Coordination Strategies

A. Centralized Strategy

In the centralized strategy, the control station is responsible for making the decision and ensuring coordination among mobile robots. We assume that the control station possesses a global knowledge about the environment of interest (i.e. location of robots, sensor nodes location, and location of intruders). To that end, the control station is assumed to receive continuous update of system states. When a sensor node detects an intruder, it estimates its current (x; y) position and sends an alarm to the control station through the WSN infrastructure. As the central agent already possesses up-to-date information about the environment, it uses its global knowledge to find an (near) optimal solution to follow and capture the intruder(s) by the mobile robots. This mechanism can be seen as an instance of the Travel Salesman Problem (TSP) or the Shortest Path Problem that are NP-Hard problems, whose complexity depends on the number of acting agents (i.e. pursuers and intruders). In order to find the optimal assignment, the control station calculates the cost that pays each robot to reach the intruder. The cost is the path length that separates the current intruder's position from the robot. The cost is calculated using a path planning algorithm. The best assignment is the one with the minimum cost, i.e. shortest path. After evaluating the necessary cost for all the robots, the central unit sends command to the winner robot (the robot that has the lowest cost) either directly (through WiFi connection) or via the wireless sensor network to start tracking the intruder until capturing it. During the mission, the WSN keeps updating the control station with the new intruder's location periodically, and feeding it with other potential changes of the environment (e.g. penetration of another intruder). Fig. 1 shows the centralized strategy process. The main problem of this approach is its tractability for a large-scale system where information gathering will be much harder than with small teams. In addition, this strategy is demanding in terms of communication overhead and would not be reactive to fast changes. This approach also suffers from the typical single-point-of-failure problem as it heavily relies on the central control station. However, the advantage of this approach is that it can provide very accurate solutions as it is based on global knowledge of the environment.

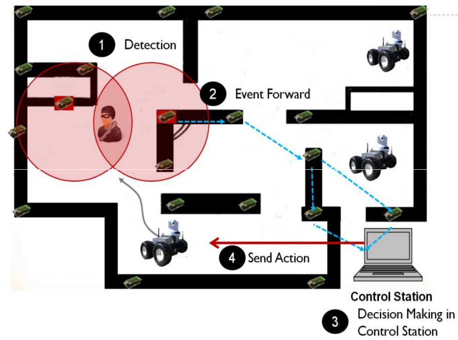

Fig. 1. Centralized Strategy

B. Distributed Strategy

In the distributed strategy, the control station does not necessarily have recent state information of the network status Even if a recent state is available; the decision will be made distributed in the robot team side and not commanded by the control station. The distributed strategy is illustrated in Fig. 2.

Unlike the centralized strategy, once an intruder is detected by sensor nodes, an alarm will be directly sent, not only to the control station, but also to each pursuer robot through the WSN infrastructure. A robot that receives the alarm will decide whether (or not) to follow the intruder based on the information it has collected from the environment (its location, location of the intruder, etc). The limitation of this approach is that, in some cases, a subset of mobile robots can follow the same intruder since each robot acts autonomously and makes

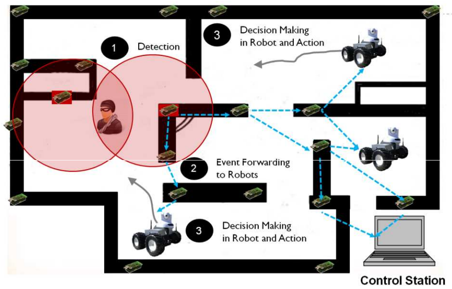

Fig. 2. Distributed Strategy

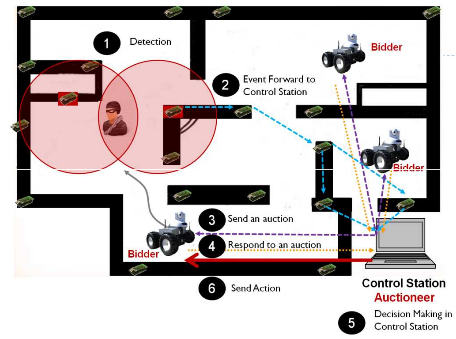

Fig. 3. Market-Based Strategy

its decision independently of other robots, since it does not have a global knowledge about the other robots deployed in the same environment. A major challenge is to specify intelligent heuristics to help on taking efficient robot-initiated decisions based on its local information. In fact, it is unwise that all robots receiving an alarm should go into action independently of their locations and that of the intruder(s), but only those who are most likely to capture it (them) are supposed to go for the mission. The distances and paths between robots and intruders will play an important role in taking such decisions. The kinematics of robots, the number of robots in the team, the speed of intruders and their number are also other parameters that might play a role for optimizing the decision making process. Sensor nodes will bring more intelligence to the application by providing continuous information update of changes in the environment (e.g. robot's location, intruders position) helping the robots to improve their visibilities of the environment and relative changes. This significantly improves the system performance as compared to autonomous robotic team with no WSN support since robots will not be able to communicate all the time due to their restricted communication range. In contrast, with the support of the WSN, communication is always possible between robots through the WSN making the coordination more effective. The control station will mostly have a passive role in the distributed approach; however, it can still feed the robots with useful information it might collect to optimize their plans.

C. Market-Based Strategy

The market-based approach provides a good trade-off between centralized and distributed strategies. It eliminates the need for global information maintenance at the control station, while it provides more efficient solutions as compared to distributed approach [3]. The market-based strategy is shown in Fig. 3.

Once an intruder is detected, sensor nodes will notify the control station. In this approach, the control station will not search a solution based on its local information, but will act as an auctioneer asking for the best price to accomplish the intruder tracking and capturing task. In this strategy, the control station will initiate the announcement phase in which it sends an auction to all available robots, informing them about the list of intruder(s) and its (their) location(s). Each robot receiving the auction will make an offer for these intruders by submitting bids to the control station. When the control station receives all the bids or a predefined time has passed, the auction then passes to the winner determination phase and the control station decides which intruder(s) to allocate to which robot(s). The robot with the lowest bid for tracking a particular intruder is selected.

TABLE I
MOBILE ROBOTS (PURSUERS AND INTRUDERS) CHARACTERISTICS

		Pursuer Robots	Intruder Robots
Minimun	Translational Speed	0.05 m/sec	0.0 m/sec
	Rotational Speed	30 deg/sec	0 deg/sec
Maximum	Translational Speed	3 m/sec	0.4 m/sec
	Rotational Speed	30 deg/sec	30 deg/sec
distance to avoid obstacles		0.5 meter	1 meter

IV. SIMULATION EVALUATION

A. Simulation Model

This section presents the performance evaluation study of the three proposed coordination strategies using the well-known Player/Stage robotic simulator. Each simulation scenario was repeated 30 times. A set of mobile pursuers are deployed in the area in different locations. For each scenario, we change the number and the location of the pursuers and the initial robots locations to randomize the initial system state. We modeled an intruder as a mobile robot, but with properties different from those of the pursuers as shown in Table I. The sensor nodes used in the simulation are modeled as static robots, whose purpose is to detect intruders using their laser range sensors. The properties of the laser sensors are depicted in Table II.

To evaluate the proposed strategies under different settings, we designed several scenarios, in which we varied the number of pursuers and the number of intruders. Our objective is to assess the proposed strategies in three different situations: (1) the number of pursuers is greater than the number of intruders, (2) the number of pursuers is smaller than the number of intruders, (3) the number of pursuers is equal to the number of intruders. We studied the impact of this variation on the average traveled distance per robot, and the mission time as metrics of interest. The traveled distance in each simulation run is averaged over the number of pursuers. As shown in

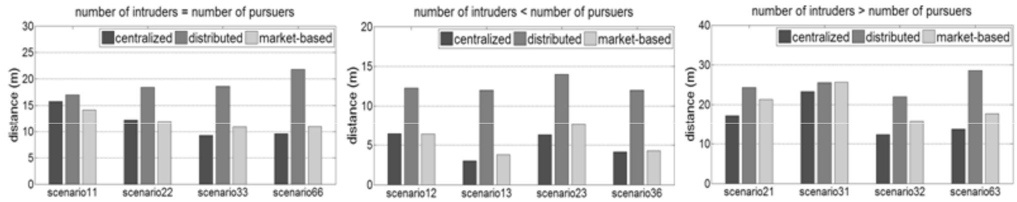

Fig. 4. Average Traveled Distance per Robot

TABLE II
SENSORS CHARACTERISTICS

minimum range	maximum range	field of view	color
0 meter	8meters	180 deg	green

the x-axis of Fig. 4, simulation scenarios are indexed such that $scenario_{n,k}$ means that there are n intruders and k pursuers. Note that we did not take into consideration the communication delays and we provide insights only on the pure behavior of the coordination strategies independently from the communication.

B. Simulation Results

Fig. 4 depicts the average traveled distance per robot for the three proposed coordination strategies. As expected, the distributed approach results in longer paths for capturing the intruders as compared to centralized and market-based approaches. This is due to the non optimality of local decision taken by the robots in an ad-hoc fashion. The difference becomes even more featured when the number of intruders is smaller than the number of pursuers. This particular case seems to be less complex than the two other cases, and the centralized and market-based approaches are able to quickly find efficient near optimal solution to the problem in the former case. The difference between centralized and market-based approaches is not significant, although the centralized approach provides the lowest cost in most scenarios. Fig. 5 shows the average mission time for the three approaches. The mission time for each strategy was calculated based on the average mission times of all scenarios. We observe that the centralized approach exhibit the smallest mission time with the smallest variation, which is natural as it calculates the most optimal solution for target capturing. On the other hand, the distributed approach not only has the greatest mission time but highly variable, which means it varies a lot from one scenario to another, in contrast to centralized and market-based whose mission times seem to be less dependent on the scenario.

V. CONCLUSION

In this paper, we addressed the problem of robot-sensor coordination in a surveillance application and proposed three strategies, centralized, distributed and market-based. We conclude that centralized and market-based approaches were shown to perform better in terms of traveled distance and mission time than the distributed strategy. This comes at the expense of assuming global knowledge of the system status in

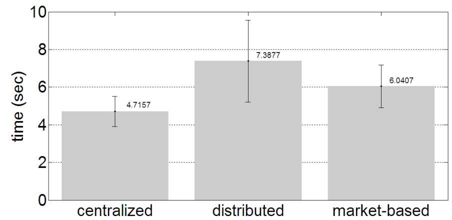

Fig. 5. Mission Time

the case of centralized and market-based approaches. These results did not consider the communication overhead, which impacts the performance of these three strategies. This issue is planned as a future work as it is important to quantify the impact of communication, mainly on the mission time.

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