



Selective Smooth Fictitious Play: An approach based on game theory for patrolling infrastructures with a multi-robot system



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ABSTRACT

The multi-robot patrolling problem is defined as the activity of traversing a given environment. In this activity, a fleet of robots visits some places at irregular intervals of time for security purpose. To date, this problem has been solved with different approaches. However, the approaches that obtain the best results are unfeasible for security applications because they are centralized and deterministic. To overcome the disadvantages of previous work, this paper presents a new distributed and non-deterministic approach based on a model from game theory called Smooth Fictitious Play. To this end, the multi-robot patrolling problem is formulated by using concepts of graph theory to represent an environment. In this formulation, several normal-form games are defined at each node of the graph. This approach is validated by comparison with best suited literature approaches by using a patrolling simulator. The results for the proposed approach turn out to be better than previous literature approaches in as many as 88% of the cases of study. Moreover, the novel approach presented in this work has many advantages over other approaches of the literature such distribution, robustness, scalability, and dynamism. The achievements obtained in this work validate the potential of game theory to protect infrastructures.

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1. Introduction

Multi-robot systems have recently become a focus of considerable interest due to their applicability in several areas. Generally speaking, a multi-robot system is defined as a set of homogeneous or heterogeneous robots, which operate in the same environment. However, robotic systems may range from simple sensors, acquiring and processing data, to complex human-like machines, able to interact with the environment in fairly complex ways. Currently, these systems represent a field of research within robotics and artificial intelligence (Farinelli, Iocchi, & Nardi, 2004). This field is focused on designing solutions to coordinate the decision-making among robots. There are several advantages of multi-robot systems over single-robot systems. Firstly, a multi-robot system performs a given task more efficiently. Secondly, multiple robots increase robustness and reliability. Thirdly, multi-robot systems enhance performance in complex and distributed tasks. Finally, several robots with limited capabilities are cheaper and easier to build than a single powerful robot (Parker, 2008).

The multi-robot systems can be used to solve several applications in adversarial domains such as robotic security (Velooso & Nardi, 2006). In these domains, a robotic security platform represents a powerful defensive tool for mitigating threats (Everett,

2003). The multi-robot patrolling problem addresses a task within robotic security. In this task, a group of robots visit points of interest defined around an area for security purpose (Portugal & Rocha, 2011a). A fair solution for this problem must reduce the time between two visits to the same point (Chevalyere, 2004) as well as avoid predictability.

The multi-robot patrolling problem has received much attention in recent years, specially works that develop algorithms to coordinate decision-making among robots (Portugal & Rocha, 2011a). Those works have implemented different principles such as reinforcement learning (Santana, Ramalho, Corruble, & Ratitch, 2004); negotiations methods (Menezes, Tedesco, & Ramalho, 2006; Hwang, 2009); swarm optimization (Glad & Simonin, 2008; Chu & Glad, 2007; Wagner, 2000; Glad & Buffet, 2009); cycles and partitioning (Chevalyere, 2004; Elmaliach, Agmon, & Kaminka, 2007; Portugal & Rocha, 2010, 2011b); and adaptive solutions (Sempé & Drogoul, 2003; Chu & Glad, 2007). A description of all of them can be found at a recent survey in Portugal and Rocha (2011a).

The results obtained by those works have demonstrated the effectiveness of the methods that implement solutions based on cycles and partitioning (Menezes et al., 2006; Chevalyere, 2004). The suitable performance of those methods can be explained by their centralized coordinator scheme (Almeida et al., 2004). However, those methods have three disadvantages. Firstly, a centralized solution has several problems such as lack of scalability, low

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reliability, absence of self-organization, high computational load and susceptibility to single-point failure. Secondly, the deterministic nature of those methods are not suitable for security purpose due to their predictability. Finally, those methods require to know the whole information of the environment to determine a path for each robot. However, such information is not always available beforehand.

This paper describes a novel method based on Smooth Fictitious Play (Fudenberg, 1998) to solve the multi-robot patrolling problem. Smooth Fictitious Play is an iterative model of game theory with which a group of robots interact. In this model, each robot makes its decisions taking into account the historical frequency of the past decisions of other robots. The method presented in this work has three advantages over other methods of the literature. Firstly, the stochastic nature of Smooth Fictitious Play makes this method non-deterministic, which is suitable for security purpose. Secondly, the robots do not have defined routes in this method. As a result, the whole information of the environment it is not needed beforehand. Finally, the absence of a central coordinator makes this method distributed, fault-tolerant, and dynamic.

In the literature there are several works that use concepts of game theory for security purpose. For instance, a method of game theory called iterated elimination of dominated strategies is used to minimize the infiltration ratio of an attacker (Aguirre et al., 2011). In another work, a statistical analysis is carried out to obtain the optimal strategies of a game to protect valuable goods against attackers (Bruni, Nuño, & Primicerio, 2012). Finally, the so-called Stackelberg security games are used to model the interaction between a defender and an attacker to protect infrastructures such as Los Angeles International Airport (An, Kempe, Kiekintveld, & Shieh, 2012). All those works use game theory to model the conflicts of two rational decision-makers i.e., a defender and an attacker. To this end, all of them use zero-sum games.

As aforementioned, this work uses game theory to solve a security problem. However, the manner in which the concepts of game theory are used differs greatly from other works. There are four differences to highlight. Firstly, constant-sum games are used instead of zero-sum games. Secondly, several constant-sum games are defined throughout an environment. Thirdly, the defined games are used to obtain patrolling paths to protect an infrastructure. Finally, the rational decision-makers do not have conflict interest, but their sole objective is to improve the performance of the group as a whole. To the best of the knowledge of the authors, this is the first attempt to use the concepts of game theory in this manner.

Section 2 of this work describes the methodology utilized to solve the multi-robot patrolling problem. Section 3 presents the evaluation and experimental results and section 4 discusses these results. Section 5 concludes this work.

2. Material and methods

Game theory considers a situation where several players are engaged in a repeated play of a game in strategic form. These players chose strategies considering the strategies chosen by other players in previous stages. The outcome of this iterative procedure is known as of the Nash Equilibrium of the game. In order to understand this procedure, this section describes the methodology used to solve the multi-robot patrolling problem. The first part of this section discusses concepts of game and graph theories, whereas the second part describes the model implemented.

2.1. Game theory and graph theory concepts

Fig. 1 shows an environment in which a set of robot are engaged to carry out patrolling tasks. In this figure, big black circles stand

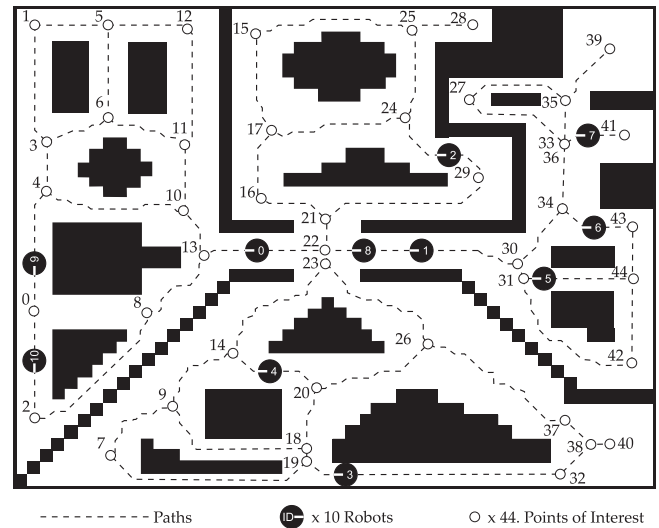


Fig. 1. Example of a strongly connected environment used to carry out multi-robot patrolling task.

for robots, small white circles represent nodes or points of interest to be visited, and dotted lines represent paths.

This environment was represented using an undirected weighted graph G . This graph is an ordered pair consisting of a set $E(G)$ of edges and a set $N(G)$ of nodes. The nodes of this graph stand for specific points of interest, whereas the edges represent paths by using numbers corresponding to the cost, proportional to their lengths. However, in some circumstances, the cost can also take into account another factors such as energy consumption, time required to reach the point and so on. The main advantage of this representation is its applicability, i.e., it can be easily used in other domains such as computer networks, distributed coverage, and so forth (Almeida et al., 2004). In the patrolling domain, a group of robots must visit the nodes in such a manner that the time between two visits to the same node is reduced. To this end, the robots have to disperse in the environment so as to avoid getting stuck in small regions.

Centralized or distributed approaches can be used to achieve such dispersion. In centralized methods (Chevalyere, 2004; Elmaliaich et al., 2007; Portugal & Rocha, 2010, 2011b) direct interaction among robots does not exist, whereas the opposite is true in distributed approaches. In the approach presented in this work, such interaction takes place at each node of the graph. Thus, at each node, the robots have to decide the next action, i.e., the next node to visit, taking into account the past decisions of other robots. Considering such interaction, a number of normal-form games were defined at each node.

Formally, a finite n -robot normal-form game Γ consist of:

- A finite set R of r robots, indexed by i .
- A finite set $A = A_1 \times \dots \times A_r$, where $A_i = \{a_i^1, \dots, a_i^k\}$ is a finite set of actions for robot $i = 1, \dots, r$. Each vector $a = \{a_1^1, \dots, a_r^1\} \in A | j_{1, \dots, r} \in \{1, \dots, k\}$ is called *action profile* for the game Γ . Each action is related to an edge $e \in E(G)$.
- A finite set $S = S_1 \times \dots \times S_r$, where $S_i = \{s_i^1, \dots, s_i^k\}$ is a finite set of strategies for robot $i = 1, \dots, r$. Each vector $s = \{s_1^1, \dots, s_r^1\} \in S | j_{1, \dots, r} \in \{1, \dots, k\}$ is called *strategy profile* for the game Γ . A strategy is the criterion taken into account to determine the action to be selected.
- A payoff function $\pi_i : S \rightarrow \mathfrak{R}$ for robot $i = 1, \dots, r$, where S is the set of strategy profiles. Therefore, $\pi_i(s)$ is the payoff of robot i when strategy profile s is chosen.

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