Effective Cooperation and Scalability in Multi-Robot Teams for Automatic Patrolling and Inspection of Infrastructures

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Ph.D. Thesis Project

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Abstract

This Ph.D. Thesis Project falls under the area of robotics, more specifically it addresses cooperative multi-robot systems in patrolling missions, which is a recent field of research. Multi-robot patrol is a task where agents must coordinately visit all regions of an area, at regular intervals, in order to protect or supervise them. The major motivation for studying this issue relates to its wide spectrum of applicability and the potential to replace human operators in dangerous or tedious real-life scenarios.

During the last decade, diverse multi-agent patrolling strategies to solve the problem have been presented. Every strategy proposed is distinct and is normally based on operational research algorithms, simple and classic techniques for agent coordination or alternative, and usually more complex, coordination mechanisms like market-based approaches or reinforcement-learning. The variety of approaches presented differs in various aspects, such as the agent type and their decision-making, the coordination and communication mechanisms, their ability to scale to larger team sizes, robustness and even the representation of the environment. Despite this diversity, there are still well-known limitations in previous works that should be overcome. Like for example, the feasibility of many approaches merely on virtual environments with software agents, the lack of study on the ability of the team of robots to scale, the lack of experimentation with real mobile robots and even the major simplifications assumed in diverse works.

Considering the current work concerning the patrolling problem with a team of multiple cooperative robots, it is felt that there still is a great potential to take a step forward in the knowledge of this field, approaching the weaknesses of previous works, by presenting innovative ideas and important scientific contributions.

The work plan of the upcoming Ph.D. studies is divided in two main stages. Firstly, the scalability of the team of robots using different strategies and environments is analyzed
in order to formulate a mathematical model considering the system’s variables, becoming the first known study of this type applied to the patrolling context. Also, it is intended to present a method for automatic estimation of the optimal team size with respect to a given optimization criterion. In the second main stage of the work, it is intended to propose a new cooperative and possibly distributed strategy for patrolling infra-structures. This innovative strategy will be validated through simulations as well as practical experimentation using a homogeneous team of robots in a real scenario.

**Key Words:** Multi-Robot Patrol; Cooperation; Scalability; Topological Maps; Graph Theory.
Declaration

The work in this thesis project is based on research carried out at the Mobile Robots Laboratory of ISR (Institute of Systems and Robotics) in Coimbra, Portugal. No part of this thesis has been submitted elsewhere for any other degree or qualification and it is all my own work unless referenced to the contrary in the text.

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Chapter 1

Introduction

This Thesis Project is intended to present the work on the author’s Ph.D. studies in the Mobile Robots Laboratory (MRL) of the Institute of Systems and Robotics (ISR) in Coimbra for the next couple of years. The work domain is multi-robot systems; more specifically patrolling missions with teams of mobile robots, and the main aspects herein addressed are patrolling strategies, agents’ scalability and applicability in real-life situations.

It starts by presenting the context of the research to clarify the motivation and the importance of studying such problem. Also, some guidelines about multi-robot systems in general and, more specifically, the patrolling problem are herein introduced. This problem is first defined and is carefully analyzed throughout this document, in order to establish and justify the objectives of the work and propose important scientific contributions. Finally, in this chapter, an overview of the document is given.

1.1 Context and Motivation

In recent years, robotics has been one of the fields with the most substantial advances. Within the diverse areas that it embraces, mobile robotics has had great focus in the last decades from Roboticists (i.e., researchers on robotics) around the world. In particular, issues like autonomous navigation, path planning, self-localization, coordination and cooperative dynamics, mapping, exploration, surveillance, object detection, pursuit-evasion and coverage, which benefited from the progress of artificial intelligence, control theory,
1.1. Context and Motivation

computer vision, real-time systems, sensor’s development, electronics, communication systems and system integration.

Nowadays, we expect to see robots with many different shapes operating in different environments as on land, underwater, in the air, suspended on wires, climbing and so on. This evident growth is extremely motivating for the development and contribution of new approaches by the community.

In particular, multi-robot patrolling is considered as a contemporary area with some relevant work presented in the last decade, especially in terms of strategies for coordinating teams of mobile robots. However, many of these studies present unrealistic simplifications, strong limitations or questionable applicability as it will be illustrated later on.

Therefore, there is an eminent potential to explore in this context.

A crucial question is: “Why is it important to study the Patrolling Problem?” Similarly to other studies on robotics like [Debenest et al., 2009] or [Marjovi et al., 2009], multi-robot patrolling is a task with the potential to replace human operators in dangerous real-life situations like, mine clearing or rescue operations in catastrophic scenarios. The domain of applications is vast. However, replacing human operators is not intended to generate social controversy, as for instants, by increasing future unemployment rate. The idea is to safeguard human lives, reducing the risk to human operators in the face of dangerous scenarios or assist them in tedious and repetitive jobs similarly to industrial manipulators, by easing arduous, tiring and time-consuming tasks. Replacing people with autonomous robots in these scenarios provides inestimable benefits. Furthermore, it can be difficult to coordinate human teams to guarantee that the area is free of intruders. This suggests using robots specially equipped for assistance, offering the possibility to relieve human beings, enabling them to be occupied in nobler tasks like, for example, monitoring the system from a safe location.

Also, the patrolling problem is very challenging in the context of multi-robot systems, because agents must navigate autonomously, coordinate their actions, be distributed and acquire information about the space, may have communication constraints and must be independent of the number of robots and the environment’s dimension. All of these characteristics result in an excellent case study in mobile robotics and conclusions drawn from such studies may support the development of future approaches not only in the patrolling
domain but also in multi-robot systems, in general.

1.2 Multi-Robot Systems (MRS)

During the last two decades, researchers in the field of mobile robotics have begun to investigate problems that involve multiple robots rather than using single robots. In many applications, an autonomous mobile robot equipped with different sensors may adequately achieve an assignment. However, in most cases, it proves to be more expensive, less efficient and less robust than using a multi-robot system. In some cases, due to the need of combining different tasks and the dynamics of the environment, it is only viable to achieve the mission with a multiple distributed autonomous robotic system. According to [Rocha, 2005], "For some robotic tasks, especially those that are intrinsically distributed and complex (...), a team of several cooperative mobile robots - a cooperative multi-robot system - is required to either make viable the mission accomplishment or, at least, accomplish the mission with better performance than a single robot".

Some characteristics of multi-robot systems include distributed control, autonomy, communicative agents and greater fault-tolerance. A single robot may be vulnerable to hostile environments or attackers, for example, in military actions. In such scenarios, agents would greatly benefit from the assistance of nearby agents during emergencies, failures or malfunctions.

Also, another important advantage is the possibility of having many robots in numerous places, carrying out diverse tasks at the same time, i.e. space distribution. Most missions are solved much quicker if robots operate in parallel. Increasing robustness and reliability of the solution is also feasible in MRS by introducing redundancies in the capabilities across robot team member and graceful degradation, remaining functional if some of the agents fail.

From the cost-effective point of view, it may actually be cheaper and more pragmatic to build a set of less capable and simpler robots that can cooperate, instead of one single robot to perform the entire mission, depending on the intended application.

In more complex problems, which require solving distinct tasks in different locations of the environment, it can be useful to divide the problem in simpler subtasks and assign them
1.2. Multi-Robot Systems (MRS)

Figure 1.1: Example of teams with multiple robots.

to different robots of the team. Task decomposition together with effective cooperation can be a major advantage of a multi-robot system, if correctly designed. This feature can be used, for example, in exploration of unknown environments. To increase reliability and robustness, in comparison to a single autonomous mobile robot incorporated with all kind of sensors and abilities, a team of multiple robots may be heterogeneous by having spread resources.

As studies go on, the complexity of the presented multi-robot systems has been growing. Multi-robot teams are expected to respond robustly, reliably and adaptively in unknown and dynamic environments, mechanical or communication failures, learning of new skills or addition of new robots.

One of the main difficulties when approaching these systems is to coordinate many robots to perform a complex, global task in an efficient manner, maximizing group performance under a wide range of conditions, with flexibility to take advantage of the resources available, embrace the requirements and constraints imposed and resolve issues like action selection, coherence, conflict resolution and communication. This cannot be done by just increasing the number of robots assigned to a task. A coordination mechanism must exist to establish relationships between agents in order for them to complete the job.
1.3 The Patrolling Problem

Patrolling an infrastructure with multiple robots is no different than other multi-robot assignments; in the sense that it incorporates all the previously mentioned characteristics of MRS. To understand this problem, it is important to introduce the definition of patrol. To patrol is “the activity of going around or through an area at regular intervals for security purposes”, according to the Webster’s online dictionary [Webster’s, 2010]. In this case, instead of having a human guard or a group of men, the patrolling task should be performed by multiple mobile robots in a real-life environment. Also, it is studied the activity of going through an area (i.e., area patrol) rather than going around an area (i.e., perimeter patrol).

Patrolling is seen as a somehow complex multi-robot mission, requiring agents to coordinate their decision-making with the ultimate goal to achieve optimal group performance. It also aims at obtaining information, watching over places, searching for objects and detecting anomalies in order to guard the grounds from intrusion.

Essentially, investigation on the Patrolling Problem is divided in two classes: enemy detection and supervision, as seen on Figure 1.2. Both have different goals and metrics. While a good strategy for detecting enemies does not necessarily require constant visits to all locations of the environment, a good supervision strategy intrinsically involves such visits.

Enemy detection strategies, usually called pursuit-evasion on the literature, may assume mobile or motionless targets. The goal is to detect the target as quickly as possible and the strategy performance may be evaluated through exploration time or using other met-
1.3. The Patrolling Problem

rics. Pursuit-evasion will be briefly addressed further on.
The focus in this work is on monitoring and supervision of environments, which involve frequent visits to every point of the infrastructure, and the words “Patrol” and “Patrolling”, are implicitly used in this sense throughout this document.

Some distinct area patrolling strategies for teams of multiple robots have been presented in the last decade, as it will be seen in the next section. It is consensual that a good strategy should minimize the time lag between visits in strategic places of the environment, with many authors using metrics based on idleness to gauge the performance of their strategies.

Also, it is important to address the characteristics of the patrolled environment. For example, the environment may be static or dynamic, i.e., there may be changes in the environment during execution of the mission due, for example, to mobile obstacles. In these cases, the agents have to keep track of all changes and update their local representation of the environment. There may be also areas of the environment with different patrolling priorities if, for example, a region is more critical or more susceptible to attacks than others. In this case, such regions will need to be visited more often.

Robotic agents are normally endowed with a representation of the environment, which is typically an occupancy grid model, which in turn, is normally abstracted by a simpler, yet precise representation: a topological map (i.e., a graph).

As it is shown in the next chapter, most of the previous works in this field are based on topological representations of the environment. Having a graph representation, one can use vertices to represent specific locations and edges to represent the connectivity between these locations. The multi-robot patrolling problem can, thus, be reduced to coordinate robots in order to visit all vertices of the graph ensuring the absence of intruders or other abnormal situations, with respect to a predefined optimization criterion, e.g. the average frequency of passage in the vertices of the graph.

Beyond their representation of the environment, it is important to consider other properties of the robotic team like their perception, which is not necessarily global. Agents may only have local awareness of the environment around them, which, in general, makes the problem harder to tackle and more dependent on complex communication mechanisms towards updating knowledge about the state of the environment and teammates. Moreover,
1.3. The Patrolling Problem

it is important to establish this communication mechanism. Agents may need to share
state information, communicate their intentions, negotiate patrolling regions with other
agents or exchange other information that might be important, considering the strategy
proposed to better achieve their goals or the team’s goals. In order to do that, they must
respect a communication protocol, which can be accomplished, for example, through ex-
plicit messages between them or using a blackboard scheme. However, some strategies
proposed in the literature do not use communication between robots at all, like many
which use a centralized coordinator unit to compute the strategy and assign tasks to each
robot, having the sole responsibility of coordinating all agents of the team. Regarding
coordination, these strategies are called centralized. Those that do not rely on a central
unit are called decentralized or distributed and benefit from greater robustness to agents’
failures.

In addition, on any given team of robots, all agents may be the same type or not. For
example, in a centralized strategy it may be appropriate to have a heterogeneous team
of robots, where the central coordinator would assign different specific tasks according
to each agent’s distinct capabilities. Using a homogeneous or heterogeneous architecture
is a decision that relies on the actual cost of the multi-robot system and the eventual
performance of the team. It is yet left to be proven which organization is advantageous
in this context.

In this work we study, above all things, patrolling architectures in static environments,
their design, effectiveness and potential to scale to larger team sizes. Leaving secondary
questions, like dealing with intruders or monitoring changes in the environment for future
work

According to [Sempe and Drogoul, 2003], “A good collective architecture should adapt
itself to the robots group size and environment size and topology because some robots
may break down and some areas may be temporarily restricted”. The authors refer to
the scalability of a multi-robot system, which is one of the crucial points addressed in the
envisioned studies.

In the context of multi-robot patrolling, scalability consists on how well a given strategy
performs as the dimension of the team grows and how the individual productivity of each
robot is influenced by the increase of several number of agents in the team. Scalability
of the team of robots should not be mistaken for scalability of the environment. The latter refers to how easily an approach scales with the increase of the dimensions of the environment. In this work, the word “Scalability” is related to team sizes.

Furthermore, in terms of performance of the group as a whole, both efficient and effective cooperation are intended to be achieved. “Efficient” refers to the resources used in the patrolling strategy, both computational as well as physical. On the other hand, “Effective” is related to the actual results obtained using any strategy, considering a predetermined optimization criterion. An approach which obtains great results but is computationally expensive is an effective approach but not an efficient one.

All these concepts and issues are essential to lay the groundwork to approach the patrolling problem and are invariantly addressed along this work.

1.4 Proposal Structure

This Thesis Project is organized in five different sections. The first chapter introduces the context of the work and the motivation to study this issue. It also describes the characteristics of multi-robot systems, the advantage of using them, and introduces basic concepts of the multi-robot patrolling problem to launch the discussion throughout the rest of the document.

Chapter 2 reviews the most relevant research work previously carried out in the area of multi-robot patrolling, leaving works on related issues, like map representation, navigation, communication, coordination, fault detection and tolerance, enemy detection and scalability, to be analyzed in chapter 3.

Chapter 4 presents some innovative ideas to explore in this context, overcoming weaknesses of previous works and proposing relevant envisioned contributions for the upcoming Ph.D. studies. Also, the work plan for these studies is presented.

To finish, a final chapter sums up the work and provides final conclusions. The previous works referred in this document are presented in a separate bibliography section.
Chapter 2

State of the Art on Multi-Robot Patrolling

In this chapter a survey of multi-agent patrolling strategies described in the literature is presented. As stated before, this is a recently growing field, which picked the interest of the robotics community, during the last decade, mostly because of the variety of possible approaches and the potential applications of such algorithms in areas like surveillance (e.g., in industrial plants, storage areas or military camps), waste cleaning and monitoring (e.g. in sewerages or floor cleaning), defense and civilian applications (e.g., rescue operations or mine clearing) or even in computer systems (e.g., computer network administration or computer wargame simulations). Many of these applications can replace human operators in tedious or dangerous situations in the future, assuming an important social function. In this survey, it is important to notice that the words “agent” and “robot” are usually interchangeable. However, “agent” accounts for any intelligent individual, having a general scope referring also to software agents, or even human agents, beyond robotic agents. In works where the studies are not focused on robotic agents, only the word “agent” is used. The works herein referred present many differences in terms of strategy, communication paradigm, cooperation scheme, performance evaluation and other features.
2.1 Pioneer Approaches

One of the pioneer works in this field is described in [Machado et al., 2002] and in more detail in [Machado, 2002], where a discussion of multi-agent patrolling task issues is presented, as well as several architectures and various evaluation criteria. A patrolling simulator was also developed to compare these architectures.

Different agent behaviors are employed in the ten approaches considered therein, which test the ability to patrol the environment, abstracted by a graph. Namely:

- Reactive Agents (with local information) vs. Cognitive Agents (with access to global information). Cognitive agents use a shortest path technique to go from vertex A to vertex B in the graph;

- Agents using different communication mechanisms: No communication, blackboard communication, communication by flags in the environment and using a centralized coordinator;

- Random decision for choosing the next node to visit vs. Decision based on the nodes’ idleness, which can consider the individual idleness by the current agent or idleness of visits by all agents.

To analyze the performance of each architecture, the following three evaluation criteria were proposed: average idleness period of each vertex, worst idleness considering all vertices in the graph and exploration time, i.e., number of iterations to complete a patrolling cycle.

Each simulation trial can be divided in two phases: a transitory phase and a stable phase. In the former, the idleness value grows from zero to a range not affected by the initial state of the system. In the latter, there is no more influence of the initial state, values obtained result only from the architectures’ behavior. In [Machado, 2002], the transitory phase lasted 750 iterations, while the stable phase lasted the remaining 2250 iterations. Raising the agents population (up to 25 agents), increased the performance of the team in every case, except when information is shared but no coordination mechanism existed (all agents tend to go to the same vertices). In terms of comparative performance, random decision algorithms scored the worst results. Simple techniques based on vertices’ idleness
scored close results to the same technique using a centralized coordinator. Observations in [Machado, 2002] show that strategies with agents with local knowledge are more suitable for maps where access to certain areas is difficult, i.e. there are long paths that need to be traversed. The exploration time decreases with the number of agents as expected and is more or less stable in the case of the normalized exploration time, regardless of the strategy.

In general, the best strategy was "Conscientious Reactive", which is a local and reactive strategy with no communication, based on individual idleness and without a centralized coordinator. These agents have memory being conscientious of their past actions. Other good results were obtained by "Conscientious Cognitive" which is similar to "Conscientious Reactive"; however agents are no longer reactive, choosing the next vertex to visit on the global graph (instead of their neighborhood). Also "Idleness Coordinator" and "Idleness Coordinator Monitored" got good results. These strategies use a global coordinator/planner, which assigns a goal vertex for each agent based on its idleness. The difference being that in the second one the agent checks, in each step, if its goal was already attained by other agent.

There are a few weaknesses in this work. Conclusions were drawn based on only two scenarios (map A and B on Figure 2.1). Also, unweighted edges were used, meaning that agents travel from one vertex to another in every iteration, independently of the distance between them, which is a rather rude simplification. Moreover, the solutions presented are more directed to virtual agents in simulation environments as no real robots were used.
2.1. Pioneer Approaches

The problem of generating patrolling paths for a team of mobile robots, within a certain environment following a given frequency optimization criterion, is also considered in [Elmaliach et al, 2007] [Elmaliach et al, 2007]. The area patrol algorithm developed guarantees that each point in the target area is covered at the same optimal frequency. This is possible by computing minimal-costs cyclic patrol paths that visit all points in the target area, i.e. Hamilton cycles. Agents are uniformly distributed along this path and they follow the same patrol route over and over again. Movement direction and velocity constraints may change in different parts of the environment. One of the key aspects of this strategy is the fact that it is robust, being independent of the number of robots. Uniform frequency of the patrolling task is achieved as long as there is, at least, one robot working properly. Logically, the visit frequency grows when the number of robots rises. A possible disadvantage of this approach is its deterministic nature. An intelligent intruder that apprehends the patrolling scheme may take advantage of the idle time between passages of robots in some points of the area.

Another study is carried in [Chevaleyre, 2004], wherein diverse patrolling strategy classes are described and compared, focusing mostly on two graph-theory centralized planning strategies: Cyclic strategies, similar to the previously described technique and partitioning strategies, which are approaches that use segmentation of the environment and assign

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1Hamilton cycles consist of closed paths that contain every vertex of a graph, according to [Bondy and Monty, 1976].
regions to each agent in order to navigate or explore. A simple example of these strategies is presented in Figure 2.2.

A good strategy is considered to be the one that minimizes the time lag between two passages to the same place and for all places. The author makes reference to the fact that very simple strategies, with nearly no communication ability, can achieve impressive results and also, an approach that is based on partitioning the patrolling area into regions, assigning for each region a patrolling agent, can also work well.

This paper aims to answer some main questions, such as whether the existing algorithms generate optimal strategies, whether there are effective algorithms generating near-optimal strategies, and how good partitioning and cyclic algorithms are, having agents following the same fixed path with uniform distribution.

Both strategies are proposed and examined in this paper. The main conclusion presented is that cyclic and partitioning strategies have generally good performance; the first one is better suited for graphs that are highly connected or have large closed paths and the second one is better when graphs have long corridors separating regions.

2.2 Alternative Coordination Methods

In [Santana et al., 2004], the patrolling task is modeled as a reinforcement learning problem in an attempt to allow automatic adaptation of the agents’ strategies to the environment. The authors justify the choice of using such approach based on findings from previous studies, for this domain, in which previous strategies proposed perform badly with particular environment topologies, due to the topology-dependent coordination between the agents’ actions inherent to the patrolling task.

In summary, agents have a probability of choosing an action from a finite set of actions, having the goal of maximizing a long-term performance criterion, in this case node idleness. However, to make sure that agents do not interfere with each other and to ensure a satisfactory global behavior, penalties are given when agents compete for idleness on the same node.

Two Reinforcement Learning Techniques, using different communication schemes were implemented and compared to non-adaptive architectures. Although not always scoring
the best results, the adaptive solutions are superior to other solutions compared in most of the experiments using different number of agents in the team. The main attractive characteristics in this work is distribution (no centralized communication is assumed) and the adaptive behavior of agents, which can be desirable in this domain.

In [Menezes et al., 2006], a negotiation mechanism is used to tackle the multi-agent patrolling problem. In this work, agents reveal a more scalable and reactive behavior, being able to patrol infrastructures of all sizes and diverse topology types. Besides criteria based on patrolling frequency and idleness, in this work, some other important measures like scalability (in terms of environment size), stability (uniformity or variation of the nodes visited) and reactiveness (concerning performance on environments with different topologies) are introduced.

Each agent acts as a negotiator and receives a set of random graph vertices to patrol. Agents negotiate those vertices using auctions in order to change one or even two of them with other agents. Aiming to minimize visits to the same node, these agents will try to get a set of nodes in the same region of the graph. The agents' path chosen is going to the agent node with highest idleness considering the distance.

Interestingly, simulation experiments showed that, in terms of average graph nodes idleness, patrolling strategies using negotiation mechanisms with self-interested agents generally performed better than with cooperative agents using different graph topologies.

Comparing this negotiation strategy with previous patrolling strategies, the single-cycle approach (based on operation research) used was the only one that outperformed the negotiation strategy in terms of nodes idleness. However, it is important to note that the single-cycle approach depends on a centralized coordinator, being less robust to failures.

As for stability, the proposed approach presents better results than all other approaches analyzed. Also, the negotiator agent is able to run in worlds of any size. Good results were also obtained regarding reactiveness, since the agents need no learning time or path pre-computation.

The results presented in this paper were obtained through simulations. A cooperative negotiation mechanism implies global knowledge about the utility function of all agents, which can only be done in a centralized manner or continuously synchronizing the communication between all robots during runs. Like many previous strategies presented in
this chapter, it would be interesting to test a similar approach with real robots to confirm its performance in real scenarios.

In [Hwang et al., 2009], a cooperative auction system is also proposed to solve the problem of patrol planning. Robots have no reasoning abilities, so they always bid in every auction, independently of their interest. It is the system who is responsible for assigning points to the most suitable robot. If the winner of the auction becomes the robot with the maximal path length to patrol, a re-auction process will take place, in order to choose one of the winner’s points, except the new one to be auctioned again.

After performing the cooperative auction system, the proposed approach suggests a patrol path for each robot among the points they’re responsible for. The author’s evaluate their approach in a simulated environment using three criteria, which should be minimal:

- The total energy that robots consume;
- The length of the patrolling routes among robots;
- The average waiting time for visiting the points of the environment.

The authors claim that their approach has less time complexity, lower routing path cost and better workload balancing among robots. However, they do not compare it with alternative approaches. Also, they consider a somehow unrealistic simplification: the environment is represented as an open space, with no obstacles or barriers, and Euclidean distances are used to represent the length of the path among static patrol points. Collision problems while patrolling are also not considered. Nevertheless, despite its weaknesses, the proposed approach to achieve cooperation among robots is innovative and has the potential to be used in future strategies.

[Almeida et al., 2004] studies and compares existent patrolling approaches using multiple agents: heuristic agents, negotiation mechanisms, reinforcement learning techniques, graph-theory based techniques and others. The authors believe multi-agent patrolling approaches are fundamentally based on three techniques: Operations Research Algorithms, Non-Learning Multi-Agent Systems and Multi-Agent Learning. Comparisons are made by evaluating the approaches’ performance using different topological maps. Benefits and disadvantages of each one are specified. We observe that the best strategy depends on the topology of the environment and the agents’ population size.
2.2. Alternative Coordination Methods

Generally, it was concluded that the cyclic approach, based on the Traveling Salesman Problem, has the best performance for most cases. This can be explained by its disciplined coordination scheme, which is very effective. However, this architecture will have problems in dynamic environments, graphs with thousands of nodes (due to the complexity of computing a cycle in these cases), graphs containing long edges, and patrolling regions with different assigned priorities, due to its predefined and fixed nature. On the other hand, pioneer agents studied generally have the worst performances. Firstly, agents moving randomly achieved very bad results. Secondly, agents with no communication ability, whose strategies consisted of moving towards the vertex with the highest idleness, performed nearly as well as the most complex pioneer algorithm implemented. In general, the Heuristic Agents and Reinforcement Learning techniques considered have the second best performance, followed by the considered Negotiation Mechanisms techniques.

The first known patrolling approach, which was focused and implemented on robotic agents as opposed to software agents, was presented in [Sempe and Drogoul, 2003]. This work described a reactive and adaptive approach in which robots are distributed in regions of the environment to solve the area patrolling problem, through task data propagation. Patrolling is seen in a task allocation perspective, where each robot is assigned a different region to visit.

Robots have localization and local navigation abilities and can estimate their remaining autonomy. They send their current state to a centralized system running on a remote computer, through a wireless communication network, to compute the task strength and drive the robot through propagated data. In the experimental setup, battery recharges are taken into account, unlike the software agents’ case, and physical interference can occur.

The authors claim that efficient patrol is achieved, considering an evaluation criterion based on idleness of the vertices of the topological environment, and interesting properties of adaptability concerning group size and the environment are shown.

Recently, swarm intelligence has also been used to tackle the multi-robot patrolling problem as in [Chu et al., 2007]. In this work, the environment is unknown and markers are used to implement indirect communication between agents. Being unknown, unlike previous algorithms, the environment is not represented by a graph. Instead, an empty grid
is used initially and it is updated continuously, where each cell may be free, occupied or unreachable.

A new algorithm is proposed, which relies on the evaporation process of pheromones dropped by agents (an indicator of time passed since the last visit). The agents’ behavior is naturally defined by moving towards cells containing less pheromone quantity. Agents have limited local perception, and follow paths according to the pheromone quantity in their neighboring cells.

Simulation experiments using different map topologies and team sizes showed that an approach with global perception is more effective in more complex infrastructures, in terms of average and the worst idleness. However, it proves to be twice as costly, in terms of computational complexity.

Due to the marking of the environment, the system self-organizes and an effective patrolling behavior emerges. As expected, the average idleness decreases with the number of agents, guaranteeing scalability.

Similarly, [Etor and Bruckstein, 2009] introduces an approach using ant-like swarm agents, where agents only have local perception and knowledge, cannot communicate directly, and use the environment to drop markers for later sensing. Although, being apparently distributed, a single agent, called "leader", runs a planning algorithm to find a path that covers the whole graph in a cyclic way, relying on Hamiltonian cycle computations. All other agents will follow this computed path, distributed in time, maintaining even gaps, using time stamps to estimate distances between agents.

The great innovation in this strategy is its robustness and fault-tolerance nature. Agents autonomously reorganize uniformly in case of breakdown in any agent and the leader will find a new patrolling route autonomously when there are changes in the graph. If the leader breaks down, an identifying stamp on the markers will get old, the team will realize it and one of the agents can replace the leader, for example, using an election algorithm.

2.3 Recent Studies

In a very thorough study, [Sak et. al., 2008] explores the concept of unpredictability in the multi-agent task of area patrol, unlike any other previous work. By applying unpre-
dictable actions in the patrolling method, intruders will not have access to the patrolling trajectory information to avoid being detected by agents. Also, partition techniques to assign different sites for each agent, are analyzed. Like many other patrolling algorithms, the environment is abstracted via a graph and the problem is reduced to visiting the vertices of the graph. The evaluation criteria considers three models of intruder behavior with increasing order of sophistication, assuming that intruders will choose a vertex and will stay some time at that location to achieve the attack:

- Random Intruder: attacks on a random vertex at a random time and achieves its goal if no patrolling agent detects it within a defined interval for the attack;

- Waiting Intruder: attacks as soon as an agent leaves a random vertex;

- Statistical Intruder: collects statistics on the period between visits on a random vertex and determines a safe timing for the attack, based on the visit history collected.

Metrics are presented in terms of probability of catching intruders with different models of behavior. The authors also propose to evaluate different sequencing algorithms, which set the rules for the sequence of vertex visits for each agent:

- Local random algorithm: the agent will choose randomly the next vertex to visit;

- Global random algorithm: the agent will choose randomly any vertex on the graph and will use the shortest path computation to reach that objective vertex from the current one;

- Original TSP: sequence generated by the TSP cycle solution of the graph (deterministic);

- TSP with local visits: similar to the previous one, however in each vertex the agent may choose a random neighbor to visit, after which it will return to the original vertex of the TSP cycle;

- TSP with local changes: agents choose for each cycle they perform to make a random change between two vertices in the visit order of the cycle;
• TSP rank of solutions: besides computing one TSP original solution, sub-optimal solutions are also computed and kept in a queue. After each cycle, the agents will choose randomly one of the computed solutions.

As for the partitioning techniques studied, the proposed three techniques were:

• Multilevel graph partitioning: partitioning scheme which creates regions with the same number of vertices;

• K-Means: Algorithm presented in [Jain et al., 1999] that partitions the graph in K clusters based on the Euclidean distance of each vertex to the prototype of each cluster;

• Agglomerative Hierarchical Clustering: Also presented in [Jain et al., 1999], it is a clustering algorithm that uses a different metric, in which close by vertices (it considers distance between vertices) should be joined in the same cluster.

Intensive simulation results, using a huge set of graphs, made evident some distinct facts. Traditional partitioning schemes are more effective against random attackers; however, non-partitioning schemes perform better when the attacker has some level of intelligence (waiting and statistical intruder). With random attackers or attackers with restricted information, the deterministic Original TSP cycle was the best solution found, because it covers all the nodes with the minimal time needed. The sequencing algorithm that performed better against statistical intruders was the TSP rank, which is non-deterministic, thus confirming the importance of unpredictability in the patrolling task. Random-based strategies for the sequencing algorithm although being very unpredictable, they have very high worst idleness values, which makes them generally useless for the patrolling problem. It is the authors’ opinion that if the terrain which is being patrolled is static and the patrolling task will last for a long time, it is probably better to compute centralized solutions with global information and calculations in the graph, as presented in the paper, due to the potential to achieve better global solutions than with a distributed strategy.

Having this in mind, the first step taken by our investigation group to deal with the patrolling problem was presented in my Master dissertation [Portugal, 2009], which studies patrolling algorithms and related issues like map representation, graph extraction,
surveillance, pursuit-evasion, coverage, navigation and exploration strategies. By analyzing these approaches, not limited exclusively to patrolling related works, a categorization of possible strategies was produced and an original, scalable, centralized and efficient algorithm was presented, called Multilevel Subgraph Patrolling (MSP) Algorithm, also described in [Portugal and Rocha, 2010].

The MSP Algorithm assumes that robots are endowed with the environment map and the ability for self-localization and navigation. The algorithm is based on multilevel partitioning of the environment map, assigning different regions to each mobile agent. Each region corresponds to a subgraph extracted from the existing topological representation. The algorithm deals, then, with effectively patrolling each region by computing paths for every robot in the assigned subgraph. To accomplish this, it searches each subgraph, using a classical algorithm for Euler cycles and various heuristics for Hamiltonian cycles, non-Hamiltonian Cycles and Longest paths.

Our algorithm was compared to a cyclic algorithm, similar to the one presented in [Elmaliach et al, 2007]. In order to carry out this comparison, a patrolling simulator, shown on Figure 2.3, was developed during the entire course of the work, which incorporates both approaches. Six different maps were used; the MSP Algorithm scored slightly better results in three cases and obtained slightly worse results in the other three cases. Given that cyclic algorithms are well-known for their performance, in terms of visiting frequency,
2.3. Recent Studies

these results are very optimistic and confirm the flexible, scalable, robust and high performance nature of our approach, which also benefits from being non-redundant, does not need communication between agents and collision avoidance between them is only needed in the frontiers of their regions.

Although not being implemented, fault-tolerance can also be added in this approach, by assigning new patrolling regions to the remaining robots, when a fault occurs in any of them. Like the cyclic algorithm, MSP is also deterministic. However, it is much more difficult for an evader to attack in this case, because it would need to keep track of every single robot local patrolling path.

In a later work, [Marrier et al., 2010] compares a reactive and a planning-based approach to solve the patrolling problem with multiple agents. The first one is proposed given the fact that reactive algorithms (e.g ant-colony) have been shown to perform well by relying on simplistic communication models.

The problem is not formulated in terms of optimizing visiting frequency on the vertices of the graph; instead, it is more focused on the information retrieval aspect of patrolling. The value of the information decreases with its age, forcing the agent to update its information on nodes as frequently as possible. Another aspect in this paper is its continuous-time formulation to allow real-valued durations.

Being adaptive, the first approach is robust in case of failures and can deal with environment changes. It is based on states and actions and the decision process relies on local and current information. The second approach tries to maximize information retrieved from the nodes of the graph in the long-term. It uses a heuristic search in the state space, using a branch and bound scheme to approximate the long term expected value of any state.

Experiments show that the algorithms perform similarly, with the planning-based slightly superior in general, because it looks further ahead than the reactive approach, which is purely local. However, the reactive approach runs much faster (many orders of magnitude of difference) suggesting that a simpler and computationally cheaper approach can be used in many applications instead of more complex strategies, which only perform slightly better.

In a work with wider scope, utilization techniques of collaborative teams of robots for
2.3. Recent Studies

infrastructure security applications are described in [Guo et al., 2007]. A distributed sensors algorithm for robots’ localization and 3D mapping is presented and, also, a motion planning algorithm for multi-robots considering the patrol scenario and response to invasive scenarios is discussed.

The proposed approaches overcome positioning systems, map-building and human robots’ trajectory planning limitations. In order to map the environment, a first stage is started by testing the navigation of robots in the area using the distributed sensors approach. After capturing all the required data from the environment, robots may operate in two different modes: Patrol Mode or Threat Response Scenario Mode.

The motion planning algorithm is executed to select effective patrol patterns based on a neural network coverage approach that takes the environment into account, where each robot becomes responsible for its patrol region. Also, during patrolling, robots may update their 3D maps to incorporate possible changes in the environment. If an intruder is detected, some robots will switch their operation mode to Threat Response Scenario and the algorithm is run to successfully respond to the threat, guaranteeing that robots reach the evader in the quickest possible way.

While some robots respond to threats, others will carry on with the patrol task and replan their trajectories to compensate for those that switched their operation mode.

Presented below, Table 2.1 summarizes the main characteristics of the architectures described in the three previous sections.
### 2.3. Recent Studies

Table 2.1: Summary of the main features of the architectures analyzed.

<table>
<thead>
<tr>
<th>Proposed Strategy</th>
<th>Type / Perception</th>
<th>Communication</th>
<th>Coordination</th>
<th>Decision-Making</th>
</tr>
</thead>
<tbody>
<tr>
<td>Random Reactive</td>
<td>Reactive / Local</td>
<td>None</td>
<td>Emergent</td>
<td>Locally Random</td>
</tr>
<tr>
<td>[Machado, 2002]</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Conscious Reactive</td>
<td>Reactive / Local</td>
<td>None</td>
<td>Emergent</td>
<td>Local Idleness-based</td>
</tr>
<tr>
<td>[Machado, 2002]</td>
<td></td>
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</tr>
<tr>
<td>Reactive with Flags</td>
<td>Reactive / Local</td>
<td>Flags</td>
<td>Emergent</td>
<td>Local Idleness-based</td>
</tr>
<tr>
<td>[Machado, 2002]</td>
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</tr>
<tr>
<td>Conscious Cognitiv</td>
<td>Cognitive / Global</td>
<td>None</td>
<td>Emergent</td>
<td>Global Idleness-based</td>
</tr>
<tr>
<td>[Machado, 2002]</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Blackboard Cognitiv</td>
<td>Cognitive / Global</td>
<td>Blackboard</td>
<td>Emergent</td>
<td>Global Idleness-based</td>
</tr>
<tr>
<td>[Machado, 2002]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blackboard Cognitiv Monitored</td>
<td>Cognitive / Global</td>
<td>Blackboard</td>
<td>Emergent</td>
<td>Global Idleness-based with Monitoring</td>
</tr>
<tr>
<td>[Machado, 2002]</td>
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</tr>
<tr>
<td>Random Coordinator</td>
<td>Cognitive / Global</td>
<td>Coordinator-Messages</td>
<td>Centralized</td>
<td>Globally Random</td>
</tr>
<tr>
<td>[Machado, 2002]</td>
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<tr>
<td>Idleness Coordinator</td>
<td>Cognitive / Global</td>
<td>Coordinator-Messages</td>
<td>Centralized</td>
<td>Global Idleness-based</td>
</tr>
<tr>
<td>[Machado, 2002]</td>
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<tr>
<td>Random Coordinator Monitored</td>
<td>Cognitive / Global</td>
<td>Coordinator-Messages</td>
<td>Centralized</td>
<td>Random with Monitoring</td>
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<tr>
<td>[Machado, 2002]</td>
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<tr>
<td>Idleness Coordinator Monitored</td>
<td>Cognitive / Global</td>
<td>Coordinator-Messages</td>
<td>Centralized</td>
<td>Idleness-based with Monitoring</td>
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<tr>
<td>Untitled</td>
<td>Cognitive / Global</td>
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<td>Centralized</td>
<td>Hamilton Cycle Computation</td>
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<td>[Elmaliach et al., 2007]</td>
<td></td>
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</tr>
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<td>Cyclic Approach</td>
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<td>Coordinator-Messages</td>
<td>Centralized</td>
<td>TSP Heuristic Calculation</td>
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<tr>
<td>Partitioning Approach</td>
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<td>Coordinator-Messages</td>
<td>Centralized</td>
<td>TSP Heuristic inside each region</td>
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<tr>
<td>[Chevaleyre, 2004]</td>
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</tr>
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<td>Black-Box Learner Agent</td>
<td>Reactive / Local</td>
<td>Flags</td>
<td>Emergent</td>
<td>Idleness-based Adaptive</td>
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<td>[Santana et al., 2004]</td>
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<tr>
<td>Gray-Box Learner Agent</td>
<td>Reactive / Local</td>
<td>Flags</td>
<td>Emergent</td>
<td>Idleness-based Adaptive</td>
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<td>[Santana et al., 2004]</td>
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<tr>
<td>Flexible Bidder Agent</td>
<td>Cognitive / Global</td>
<td>Bidding</td>
<td>Flexible</td>
<td>Idleness-based inside each region</td>
</tr>
<tr>
<td>[Menezes et al., 2006]</td>
<td></td>
<td>Messages</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two-Shot Bidder Agent</td>
<td>Cognitive / Global</td>
<td>Bidding</td>
<td>Two-Shot</td>
<td>Idleness-based inside each region</td>
</tr>
<tr>
<td>[Menezes et al., 2006]</td>
<td></td>
<td>Messages</td>
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<tr>
<td>Cooperative Bidder Agent</td>
<td>Cognitive / Global</td>
<td>Bidding</td>
<td>Auctions</td>
<td>Cooperative Idleness-based</td>
</tr>
<tr>
<td>[Menezes et al., 2006]</td>
<td></td>
<td>Messages</td>
<td></td>
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<tr>
<td>Bidder Agent</td>
<td>Cognitive / Global</td>
<td>Bidding</td>
<td>Auctions</td>
<td>SelfInterested Idleness-based</td>
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<tr>
<td>[Menezes et al., 2006]</td>
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<td>Messages</td>
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<td>Bidding</td>
<td>Auctions</td>
<td>Minimize the maximum patrol path</td>
</tr>
<tr>
<td>[Hwang et al., 2009]</td>
<td></td>
<td>Messages</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooperative Auction Directed by Winner [Hwang et al., 2009]</td>
<td>Cognitive / Global</td>
<td>Bidding</td>
<td>Auctions</td>
<td>Minimize the maximum patrol path</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Messages</td>
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<tr>
<td>Cooperative Auction Directed by Loser [Hwang et al., 2009]</td>
<td>Cognitive / Global</td>
<td>Bidding</td>
<td>Auctions</td>
<td>Minimize the maximum patrol path</td>
</tr>
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<td></td>
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<td>Messages</td>
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<td>Heuristic Pathfinder Cognitiv Coordinated [Almeida et al., 2004]</td>
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<td>Coordinator-Messages</td>
<td>Centralized</td>
<td>Idleness-based and path-finding heuristic</td>
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<td></td>
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<tr>
<td>Heuristic Pathfinder Two-Shot Bidder [Almeida et al., 2004]</td>
<td>Cognitive / Global</td>
<td>Bidding</td>
<td>Two-Shot</td>
<td>Idleness-based and path-finding heuristic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Messages</td>
<td></td>
<td></td>
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<td>Heuristic Pathfinder Mediated Trade Bidder [Almeida et al., 2004]</td>
<td>Cognitive / Global</td>
<td>Bidding</td>
<td>Auctions assisted by a broker</td>
<td>Idleness-based and path-finding heuristic</td>
</tr>
</tbody>
</table>
2.4 Perimeter Patrol

A similar problem in this domain is perimeter patrolling around a close area using multiple robots, which incorporates common aspects of multi-robot area patrolling. Below, three different approaches to this problem are briefly presented.

In [Agmon et al., 2008], the existence of an adversary attempting to penetrate into the area is assumed. Unlike other strategies, the main goal here is to build a nondeterministic patrolling algorithm. In this sense, the perimeter is divided into segments, assigning an agent for each region per time cycle. The robots’ motion is characterized by a given prob-
ability and the enemy knowledge/prediction of the patrolling scheme is limited. Three distinct robotic motion models are considered and tested. It is assumed that the intruder observes the patrolling scheme and decides to infiltrate through a place with the lowest probability for its detection. An optimal polynomial-time algorithm that maximizes that probability is described and its efficiency is proved when using the three considered motion models.

The same investigation group from the Bar Ilan University in Israel presented in [Elmaliach et al., 2008] a more realistic model which considers velocity uncertainties and accumulated error in the robot’s motion. Patrolling is investigated in this paper, from the point of view of optimizing point visit frequency. The model is analyzed mathematically and optimal patrolling parameters, like setting the number of perimeter segments visited by each robot, are deduced, given known bounds of uncertainty on the motion and three frequency-based criteria:

- Maximizing the minimal frequency;
- Optimizing average frequency;
- Maximizing frequency uniformity.

Finally, [Marino et al., 2009] proposes a fully decentralized algorithm for border perimeter patrol. The authors assume that robots have the ability of self-localization, they can sense the presence of other agents on their vicinity, they have their own safety area where other agents are not allowed to enter, they are autonomous and do not communicate with each other neither with a central unit.

The concept of actions is introduced, which is obtained by combining elementary behaviors. Once the actions of a particular task are defined, an action selection mechanism, based on a finite state machine implementation, properly selects the best action, depending on the robot’s state and sensed data. Thus, the approach is behavior-based and emergent, in the sense that global dynamic behavior derives from local interactions with no direct communication among robots.

Simulations using Player/Stage [Gerkey et al., 2003] and a team of three Pioneer 2-DX robots patrolling real-world indoors provided satisfactory results. The system ensures high scalability and is designed to be robust towards robot’s faults. Unlike many other
patrolling strategies, the system is non-deterministic due to a random variable that affects the choice of the patrolling direction of each robot. This can be crucial in the presence of an intelligent attacker; however, it does not consider maximizing a global optimization criterion, like visiting frequency in the perimeter points.

2.5 Summary

In this section, it was verified the variety of approaches that patrolling algorithms can comprise. After studying and comparing distinct approaches for the problem, it is important to establish new directions of research, in order to contribute to the advancement of the knowledge in this field. However, the focus in this work does not intend to be exclusively on the strategy adopted. Other relevant multi-robot issues should be addressed. In the next section, important related issues to multi-robot systems are studied towards covering more completely the patrolling problem and understand its implications.
In order to perform the patrolling task using teams of multiple robots, there are many different issues that need to be addressed, beyond the patrolling strategy. In this section, the agent’s representation of the environment is studied, as well as navigation, communication and coordination between robots, fault detection and tolerance, evader’s detection and, finally, systems’ scalability.

These issues are very important in the context of most multi-robot systems applications.

3.1 Map Representation and Navigation

As seen on the previous section, patrolling strategies frequently compute paths for each robot based on a topological representation of the environment. However, it is not usual to have this representation readily available; a metric representation is more common. According to [Thrun, 1998], the two major distinct paradigms produced for mapping indoor environments are grid-based maps and topological maps. Grid-based methods produce accurate metric maps, they are easy to build, represent and maintain, but they often suffer from huge space and time complexity, because of its fine resolution restrictions, which results in memory problems and also harder efficient planning, as well as navigation in large-scale infrastructures.

Topological maps, on the other hand, produce graph-like maps that can be used much more efficiently. They are simpler, permit efficient planning and do not require accurate determination of the robot’s position. In these maps, vertices correspond to important
places or landmarks, which are connected by edges that represent the paths between them. However, the inaccuracy of the method makes it harder for recognition and maintaining consistency in large-scale infrastructures, particularly if sensory information is ambiguous, which may result in perceptual aliasing, i.e., difficulties in recognizing similar places that look alike.

In [Zimmer et al., 1994], there is a focus on the constraints on navigation by mobile robots when using topological representations. The main limitations found were: "handling of very inaccurate position (and orientation) information as well as implicit modeling of complex kinematics during an adaptation phase". Since there were no distance measuring sensors in this work, it was only possible to detect neighbor vertices in the topological graph, by traversing their connections and not simply by sensing or recognizing them. Despite all these constraints, the path planning methods used in the work produced adequate results. Also, topological maps have the advantage of being often very flexible and offer a lot of alternative routes, allowing navigation replanning to be done more quickly.

In turn, [Szabó, 2004] presents a method for building a topological navigation graph on top of an occupancy grid. An occupancy grid consists of a metric representation method wherein each cell of the grid contains a probability value which indicates whether the related location is free space or part of an obstacle. It is relatively simple to implement and has an iterative nature.

To obtain the topological navigation graph from the occupancy grid, a process of skeletonization (creating vertices), followed by chaining the skeleton to form edges and graph optimization is conducted. Szabó's work was a major inspiration when producing our own method of topological representation of the environment, presented in [Portugal, 2009], which computes the Voronoi Diagram in a first stage creates the vertices by image processing and extracts the complete connectivity information of the graph in a second stage. An illustrative example of such representation is presented in Figure 3.1.

Although addressing search in an unknown environment, [Chomchana et al., 2008] presents a self-organizing method for dynamically extract a graph of the environment, based on a reaction-diffusion equation. Each node moves based on the gradient of a potential function and the equation ensures that the nodes will spread and cover the entire explored region. Also, if something changes in the environment, the pattern automatically recon-
3.2 Communication and Coordination

Coordination mechanisms between robots are essential to efficiently achieve the team’s goal. By coordinating their actions and communicating their intentions, robots can, for example, distribute themselves in an environment for a patrolling task. There is a vast

In this work, both a cyclic strategy (based on the TSP problem) and a partition-based strategy are discussed and tested for effectively patrolling the environment. The strategies proposed tries to minimize repeated coverage, the distance traveled by robots and the total time required for complete coverage. Apart from verifying the good performance using these strategies, authors also notice the improvement of performance with the increase of mobile robots in the team and finish their discussion by stating that investigation on the properties of scalability with team of robots in similar strategies is needed and is necessary to draw some conclusions on the appropriate amount of population for a specific multi-robot task.

Figure 3.1: Topological map computed in the Patrolling simulator developed in [Portugal, 2009].
3.2. Communication and Coordination

possibility of coordination techniques for multi-robot systems. The chosen approach depends on the application, on the system design (e.g. the robot's skills) and the problem's constraints. Coordination is achieved when the agents do not interfere with each other, cooperating instead, by sharing valuable information in appropriate timing during their mission as a group.

In [Sheng et al., 2006], a multi-robot coordination algorithm for an area exploration task is proposed. The coordination algorithm is based on a distributed negotiation-based approach. The range of communications between robots is limited. Hence, such limitation is considered in the bidding algorithm, by introducing a nearness measure, and robots tend to stay close to each other. Secondly, similarly to many strategies in exploration tasks, a map synchronization mechanism is proposed. The approach was evaluated by means of simulation.

The environment is modeled as an occupancy grid, which is locally updated by every robot while exploring, and shared by robots in the same subnetwork. Each robot tries to explore areas with the maximum information gain and reduce its cost, which is a function of the distance traveled from the current position to the target position – this is the main concept behind the bidding process.

Bidding between robots in the same subnetwork occurs in order to choose the best candidate motion plans, thus coordinating the team of robots. Communication delay and the map synchronization algorithm are also discussed.

According to [Julian et al., 2009], “Robots in a team need to communicate state estimates to self-organize”. Moved by this belief, they present a strategy for exchanging state estimates, which deterministically broadcasts estimates of nearby robots more frequently than distant ones.

In applications where robots are spread across large-scale domains, inter-robot distances can become larger than their capable peer-to-peer transmission range, which requires multi-hop networking to distribute state information over the entire system.

They intend to answer the question: “How important is it for one robot to broadcast state information about another robot?” by representing quantitatively this importance as a function inversely proportional to the distance between robots.

From this importance function, they developed a deterministic algorithm that ensures
state estimates propagate throughout a robot network. Instead of routing actual data packets to a predetermined receiver, state information is deterministically transmitted to be used by the entire team of robots.

Simulations with 9 robots running a distributed coverage algorithm, using real control and wireless hardware, show that the algorithm outperforms simple flooding schemes for large robot networks, being efficient in terms of bandwidth and computational complexity, and not requiring network topology information to be transmitted or computed.

On the other hand, [Hollinger and Singh, 2010] tackles the problem of coordinating a team of multiple robots with connectivity limitations. All agents must cover an environment represented as a graph and assure periodic network connectivity. Connectivity between robots is needed to communicate gathered information, plan the next step and check if all robots are still operational.

An online algorithm, without a centralized controller and that scales linearly with the number of robots, is proposed. The method outperformed several algorithms proposed in previous works – continual connectivity, market-based approaches and others – in a multi-robot informative path planning situation using a non-adversarial environment.

### 3.3 Fault-Detection and Fault-Tolerance

Most multi-robot systems are expected to be robust in the sense that the system should maintain its functionality, possibly with degraded performance, in case a subset of the robotic agents fails. In this context, totally decentralized approaches benefit from enhanced fault-tolerance when compared to centralized approaches, which may suffer from the single point of failure phenomenon.

[Verma and Simons, 2006] studies robot fault diagnosis and the importance to monitor the state of robots to detect anomalous situations. A fault monitoring algorithm, which uses Monte Carlo methods to gain accuracy, is presented. The authors argue that it is computationally efficient and handles mechanical failures and faults due to the interactions with obstacles. A particle filter approximation, which is a Monte Carlo approximation method, is used to dynamically estimate the robot and the environmental states as they change over time.
On the other hand, [Fazli et al., 2010] focused on fault-tolerance in a novel approach for multi-robot area coverage task in a known and static 2D environment represented by a graph, which is a very similar problem to the multi-agent patrolling task. A series of decompositions of the graph are employed to obtain cycles, which are then assigned to covering robots. Firstly, a technique called Constrained Delaunay Triangulation (CDT) is used to extract the graph of the environment. Then, the graph is reduced to decrease the distance traveled by each robot and improve efficiency. Afterwards, an extended version of the Prim’s algorithm [Prim, 1957], used to build minimum spanning trees of a weighted graph, partitions the graph in order to form as many partial spanning trees as the number of covering robots. Finally, cycles are built on each resultant tree to form navigating areas for each agent.

Upon failure of a robot, all of the vertices of its assigned tree are released and robots in adjacent areas will expand their trees, using the same extended version of the Prim’s algorithm, to repossess the released vertices and cover the environment again.

### 3.4 Pursuit-Evasion and Enemy Detection

Many authors study coverage, surveillance and monitoring tasks assuming that an intruder is attempting to perform an attack in a certain location of the environment. With this in mind, they created strategies to rapidly detect and clear the threat. These strategies usually assume a behavior model of the adversary. According to [Strom et al., 2010], “Solutions to the pursuit-evasion problem help search and rescue teams quickly find survivors, sendries protect against intruders, and law enforcement apprehend suspects”. This article addresses the pursuit-evasion problem on a graph and Figure 3.2 exemplifies a potential strategy.

Basically, the problem is defined as: each of the pursuers have to choose a sequence of moves that maximizes the expected reward of the entire team of pursuers. Each pursuer computes a plan and exchanges plans with their teammates moving then to a new node and planning once again.

The model presented improves the worst case bounds over previous adversarial search methods, although not guaranteeing optimality. Also, it also extends to the multiple
evaders case, scaling well as the number of total agents increases and independently of the ratio of evaders to pursuers. Real experiments on robots and simulation confirmed the effectiveness and robustness of the probabilistic pursuit strategy.

In [Katsilieris et al., 2010] the search and secure problem is considered. Given a map of a closed area, the goal is to quickly detect intruders with a team of robots equipped with omnidirectional sensors, without allowing them to escape. To accomplish this, a graph is used to represent the environment and stationary robots (called blockers) are placed in the environment to reduce the representation to a tree graph (by loop removal in the blockers area). This approach is similar to the ones used to solve the Art Gallery Problem [Shermer, 1992] and many others for pursuit-evasion problems.

The authors explain how they extract the traversability graph from the original map, which is done through triangulation and triangles merging to form large convex regions where the vertices are extracted.

Two strategies for searching the tree graph are tested: one focused on the execution time using a high number of robots and a slower one using fewer resources. These strategies are concerned with vertex contamination, leaving no searcher-free path to a vertex, after the searcher visit, and the main goal is to secure a graph, i.e., leave no contaminated vertices in the graph. A remotely centralized computer is used to plan the strategy and integrate robots’ sensor and visual data.

Unfortunately, this approach wastes resources and does not guarantee using the minimum number of robots. However, with blockers, searching an arbitrary graph is a NP-hard
3.5 Scalability

Scalability of the robot team is also a very important characteristic for patrolling strategies. A good strategy should work independently of the number of agents in the team and with any environment topology. There have been a few scalability studies presented for multi-robot systems. In this section, two of these studies for search-related tasks are presented.

[Sweeney et al., 2003] evaluates the scalability of teams of communicating and independent robots using a distributed coordinated leader/follower search task by analyzing the schedulability of the design task structure.

In the studied search task, the leader is responsible for searching and ensuring continuous connectivity with the follower. Robots must be able to process sensor input, respond to changes in the environment and communicate with other robots. To achieve this, the control processes must be able to respond within real-time constraints.

Similarly to a collection of homogeneous processors, the distributed multi-robot system has a set of periodic tasks with data flowing between tasks on a single robot and between tasks on different robots. These tasks have predetermined deadlines, worst case computation time and also locality constraints.

The main conclusion is that communication delays in the system enforce an upper bound on the size of the robot team, which can be predicted in advance with a pre-analysis of the strategy used. With higher team sizes, there is no guarantee that messages will be able to reach their destination before the task execution, which can result in tasks executing with old data and the decrease of the system performance.

One solution proposed to this specific problem would be to redesign the system reducing the amount of communication needed between members, by using smaller messages or eliminating communication by restructuring the flow of messages (e.g. using a hierarchical structure of communication between groups of robots). The authors consider that a more complete scalability analysis should examine other factors beyond schedulability; like reliability and ease of maintenance.
3.5. Scalability

Instead, [Rosenfeld et al., 2006] presents a book chapter studying how scalability of homogeneous robots affects the productivity of a multi-robot system applied in groups with different coordination algorithms.

According to economists and conclusions from previous works on mobile robotics, groups display increasing marginal performance only until a certain group size. Beyond this point, the groups’ productivity drops with the addition of robots.

In theory, productivity should grow during size scale-up; however, spatial limitations increase the interference between robots causing the decrease of performance. Effective coordination algorithms maintain increasing productivity. To improve the group’s performance, these methods can be developed by minimizing interference between robots.

To measure the interference level with different coordination algorithms and promote comparisons, an interference variable was defined by the total time robots deal with resolving team conflicts, e.g. like replanning due to collision avoidance.

This study was first applied in the foraging domain, where robots have to locate target items from a search region and deliver them to a goal region. This domain was chosen due to the wide existing research of coordination algorithms within this environment and the likeliness of arising spatial conflicts between members of the same team in a limited field of operation. The study was limited to groups of homogeneous robots without the ability to communicate and without pre-knowledge of the environment, to minimize the factors involved in the experiment.

In order to check if the same results were obtained in different domains with restricted spatial resources, the authors also conducted similar experiences in a limited search domain where the main objective is to find the exit out of the room as quickly as possible. By evaluating exhaustive simulation trials with eight different coordination algorithms in both domains, the main conclusions were:

- The coordination method strongly impacts the scalability of the group;

- A high negative correlation between group interference and productivity was found. Besides the critical point in scalability where productivity starts to decrease, there is a second point where the addition of more robots ceases to significantly negatively affect the groups’ performance.
Authors conclude that the interference measure should be considered in future works to produce effective coordination methods with the ability to scale to larger team sizes and aid in the study of scalability qualities of robots.

### 3.6 Comments and Overview

In this chapter, some important aspects relevant to the patrolling problem, beyond the strategy used, were presented. The characteristics of the projected systems like representation, communication, coordination and robustness depends on the implementation requirements and/or the preferences of the developers. As far as this work is concerned, representation is based on topological maps. Communication, coordination and robustness are still an open issue that will considerably rely on the strategy proposed later, especially the amount of the information shared between robots. It is believed that simple interactions should be used to prevent the complexity overhead and to not affect extremely on the timing of decision-making, for example using a blackboard-type of communication.

In the next chapter, the weaknesses of previous works are analyzed to establish some priorities of research, underlining the scientific contributions for the upcoming Ph.D. studies.

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**Figure 3.3:** Results obtained in [Rosenfeld et al., 2006] using different coordination schemes in the foraging domain.
Chapter 4

Methodology

In this chapter, the weaknesses found in previous works are analyzed in order to underpin the proposal of innovative research directions in the context of multi-robot patrolling. These new research directions intend to contribute to the advancement of the knowledge on this field and assist subsequent related works, which are the main objective of these Ph.D. studies.

4.1 Weaknesses of Previously Proposed Works

Studies on the last decade revealed some crucial facts about the patrolling task: First of all, it is clearly an assignment where the utilization of teams of robots can be advantageous. Secondly, strategies to approach this problem, using multiple robotic agents, may vary in terms of the agent’s type, communication model, the coordination scheme and their strategy specific decision-making, evidenced by Table 2.1 on section 2.3. Thirdly, despite the diversity of strategies, comparative studies between approaches invariably reveal the absence of a superior approach for every case with respect to all the criteria for a good patrolling solution, since distinct approaches perform differently, depending specially on the topology of the environment.

Beyond these conclusions, the literature provides other important tools for studying the multi-robot patrolling problem, like performance evaluation criteria, environment abstraction, classification of strategies and hints for the application of the correct strategy, taking into account the connectivity and disposition of the patrol area.
4.1. Weaknesses of Previously Proposed Works

However, as seen before and underlined during the analysis made on previous approaches, there are still several drawbacks common to most architectures. It is our belief that some of these aspects need to be carefully analyzed and this analysis has the potential to represent an important contribution to the patrolling problem, by attempting to overcome these weaknesses.

Some drawbacks on previous works were documented on [Moreira et al., 2007]. These issues are still contemporary, namely:

- Lack of approaches that consider different node visiting priorities;
- Absence of a strategy dealing with dynamic environments, which suffer from disposition changes during the run;
- Absence of approaches considering energetic issues and lifetime of agents;
- No comparison between the actual time spent by different strategies to finish their patrolling cycles (typically compared by simulation runs, where each run lasts differently for each case);
- Lack of a standard environment for researchers all over the world to implement different strategies and compare precisely with previous ones already implemented.

In addition, other issues were also identified along the survey presented in this Thesis Project:

- Lack of experimental work using a team of robots in real scenarios, especially distributed ones;
- Absence of studies especially focused on scalability, complexity, flexibility, resource utilization, interference, redundancy, communication load or workload among robots when performing the patrolling task;
- Many simplifications assumed;
- Lack of diversity in the environments tested;
- Deficiency of works guaranteeing fault-tolerance;
4.1. Weaknesses of Previously Proposed Works

- Unfeasibility of many simulation approaches towards experiments with real robots;
- Deterministic nature of many centralized approaches.

In this prospected studies, it is proposed to address many of these aspects, mainly the ones which are considered more important considering the actual context. Consequently, patrolling with different priorities, dynamic environments, energetic issues and eventually fault-tolerance will be left for other opportunity.

Different priorities in the patrolling task are not crucial in this work because they can be seen as a particular case of the general problem, where some vertices require a higher frequency of visit. This could be eventually expressed in terms of idleness associated with different weights for specific vertices.

Also, it is believed that the knowledge in static environments is not mature enough to move on to dynamic situations and this would add a much higher load of complexity to the problem, because it would require the robotic agents to continuously map or monitor the changes within a structured infrastructure, re-extract the topological information, if necessary, and replan their actions. In the presented work, a static representation of the environment will be assumed.

Energetic issues will also not be our priority in the following studies. Nowadays, batteries in robotic agents tend to last for longer periods of time and there is a tendency to last even longer. A few years ago, batteries discharge could be seen as a major issue in practical implementations; however with modern robots this problem has now been attenuated and less studied. Still, it is an existing problem that ought to be considered in the future, especially for tasks which last for a long period of time. In this case, strategies have to include agents with special attention to their battery monitoring circuits, reacting when they are running low on battery and suspending their patrolling task to drive into recharge stations. This can bring lots of other questions like how should other teammates compensate for the inactivity of the recharging robot(s) or how they should schedule their visits to the recharge station to ensure continuous mission execution, depending on the strategy implemented.

Finally, robustness to failures is considered a more important issue and is still an open question depending on how the studies evolve for the next couple of years. Among other contributions, an approach for the patrolling problem, which tends to be distributed,
will be developed and, although this work focuses on coordination methods to achieve frequency-efficient patrolling with a team of mobile robots, fault-tolerance is a desired characteristic of such system and will be left open in the present time, with the certainty that will be analyzed and considered for implementation.

In the next section, starting from the other previously appointed weaknesses in past works, the main envisioned scientific contributions of these Ph.D. studies will be presented.

4.2 Objectives and Envisioned Scientific Contributions

As seen before, there are many gaps in previous works that need to be bridged. In this section, the weaknesses proposed to be overcome and details on why it is important to overcome them are presented.

Many strategies presented were compared by the authors through simulations, and their performance was analyzed based solely on algorithm runs instead of the actual time different strategies took to complete their patrolling cycles. This is seen as a limitation, because all strategies have different computational complexity and the runtime for each simulation trial is variable. For example, when a strategy produces very efficient actions, though spending too much time calculating and deciding the next move, it should be penalized in some form. Concerning simulations, it is intended in these Ph.D. studies to always analyze the actual time of simulation trials and refer not only to their effectiveness as well as to their computational complexity. Also regarding to simulations, it is very important to minimize the simplifications assumed, which is an identified drawback of preceding works as well. When too many simplifications are assumed, simulations become unrealistic and the migration to real mobile robots is a much more onerous step, not always confirming the results, because many conditions change. In the upcoming studies, unrealistic simplifications like unweighted edges on the graph, absence of obstacles or only considering certain environment topologies will not be present. In fact, the lack of diversity of environment topologies tested in previous works is also a major weakness identified. As it was referred before, it is almost an utopia to present a strategy that al-
ways performs better independently of the topology of the infrastructure to patrol. The fact is: different approaches perform differently with the environment topology. In this sense, it is absolutely crucial to evaluate the performance of new approaches using a good variety of topologies; in order to conclude in which cases one given approach is expected to patrol more effectively a given environment and which cases it is not.

In addition, many of the previous strategies proposed, especially the ones which rely on a centralized coordinator and are based on operation-research algorithms to solve the multi-robot patrolling problem, are deterministic. Most of these approaches present good overall performance in terms of minimizing the idleness of every vertex of the graph. However, they present an undesirable characteristic. Being deterministic, it is easier for an intruder to calculate and predict good areas of intrusion in the environment, because all the robotic agents will follow the same patrolling cycle over and over again. This patrolling cycle may be apprehended by an intelligent attacker and compromise the objective of the patrolling task. It is essential to explore then, strategies which comprise any kind of unpredictability to avoid similar situations. Nevertheless, conclusions drawn from previous studies showed that random approaches are almost useless in this context, thus a careful analysis should be carried to control the deterministic and unpredictability balance. Also, deterministic approaches based on operation research algorithms suffer from the computational complexity of calculating patrolling cycles in graphs with a high number of vertices. Other aspect which is also related to desired properties of the patrolling strategy is feasibility. For example, strategies which use ant-like swarm agents rely on many markers on the environment to achieve indirect communication between agents. Such strategies are usually limited to simulations, because they are practically unfeasible in experiments with real robots, mostly because of the amount of equipment required to perform experiments in a real scenario. It is the author’s opinion that feasibility is one of the key properties for a strategy to represent an important contribution to this field.

Regarding previous studies on this field, it is clear that numerous questions are still left for analysis. Many authors focused their attention purely on patrolling strategies and their effective performance. A few of them addressed different agent behaviors like self-interested or cooperative; others went further ahead, also addressing unpredictability in the patrolling task, robustness, environment scalability, stability and even reactivity.
4.2. Objectives and Envisioned Scientific Contributions

However, in this context, there are still open issues that could be studied like scalability in terms of team size, complexity, flexibility, resource utilization, interference, redundancy, communication or workload among robots using different strategies. These studies have potential to answer many questions and produce fair comparisons, in order to assist upcoming implementations and advance the knowledge towards having multi-robot systems patrolling real environment somewhere soon in the future. In this work's particular case, the focus is on scalability. Like it was specified before, scalability in this context refers to how easily an approach scales as the dimension of the team grows. This is seen as vital question in these Ph.D. studies. A good patrolling strategy is expected to perform better with the increase of the number of patrolling agents. However, the increase of effectiveness of the patrolling strategy does not necessarily means an increase of efficiency. In order to analyze efficiency when adding more agents, one should refer to the evaluation of the individual contribution of each robot with different team sizes and verify how, and especially when, the interference between agents contributes to the degradation of the individual productivity of each agent. Logically, this is expected to vary according to the patrolling architecture employed and it represents a crucial inherent property of each strategy that will influence the ability of the team of agents to scale to larger team sizes.

Perhaps the most noticeable limitation in previous works, and probably one of the main challenges in this context, is the surprising lack of experimental work using actual teams of robots patrolling real scenarios. Despite the variety of approaches presented, only a few of them were verified using teams of robotic agents, especially distributed ones. Most strategies were validated only through simulations or were directed to software agents. If we expect to use multi-robot systems in patrolling, surveillance, monitoring and exploration in future applications, it is definitely necessary to move on to mobile robotics and implement solutions using realistic scenarios. This is another important weakness that is expected to be overcome in the envisioned studies.

The work herein presented can be divided in two major stages. Generally speaking, in a first stage it is intended to develop a thorough study on the scalability of the team of robotic agents, using different strategies and environment maps, becoming, as far as our knowledge goes, the first ever study of this kind on the multi-robot patrolling problem. In a second stage, a new method which tends to be distributed is proposed and validated
in this context, taking advantage of the precedent research and knowledge about the concerned problem. More details on the work schedule will be given in the next section.

From the perspective of overcoming the weaknesses of previous work, the stages of the work program mentioned above will give the opportunity to present a careful study focused on the scalability aspects of the team of robots performing patrolling tasks, analyze an appropriate diversity of environment topologies with different connectivity constraints, without unrealistic simplifications, using weighted vertices, obstacles and considering the actual time past for the performance of the team in order to present a feasible and non-deterministic approach employing a team of homogeneous mobile robots to validate the proposed patrolling strategy experimentally.

The envisioned scientific contributions for this Ph.D. work are:

- Evaluation of the ability of a team of robots to scale to larger team sizes using diverse patrolling strategies and environments;
- Formulation of a mathematical model considering the distinct system variables;
- Method for automatic estimation of the optimal team size;
- Propose an innovative, cooperative and distributed method for patrolling infrastructures with efficient resource usage;
- Detailed description of the method to assist implementations of future strategies;
- Demonstration of the method’s feasibility by validation through an indubitable practical experimentation with a homogeneous team of robots in a real scenario.

This list of envisioned contributions is the result of an extensive analysis of the weaknesses of previous works in an attempt to fill many identified gaps. First of all, scalability of the team is an issue that was never extensively studied in the context of multi-robot patrolling. Yet, many authors assume the need to address this issue, due to the importance of the ability of the proposed strategies to scale to larger team sizes when patrolling an environment. In this work, it is proposed to take that step ahead towards studying this characteristic of multi-robot systems by considering diverse strategies on the literature and promote comparisons using different environment topologies in order to formulate
a new mathematical model considering all the system variables, like for example, the number of nodes in the graph, their connectivity, number of agents, their individual contribution, etc.

Also regarding scalability, another innovation in prospective is a method for automatic estimation of the optimal team size. This consists in calculating which should be the size of the team in order to optimize a given criterion, with a given patrolling strategy, in a given environment. This method will have the ability to achieve both effective and efficient multi-robot patrolling by offering good solutions to the patrolling problem using different strategies. For example, if we intend to calculate the optimal team size in a given environment, in order to achieve maximal individual productivity of each robot and at the same time overall effective patrolling with a given strategy, the method should compute the solution. This is seen as a pioneer idea that may prove to be an important tool to approach the multi-robot patrolling problem in the future.

After describing many existing patrolling strategies in Chapter 2, one may ask “why is it important to propose another multi-robot patrolling strategy?” Firstly, it is important to notice that are not so many distributed approaches presented in the literature. Secondly, many of these approaches proved to have good results in previous works, which lead to shift the research on this subject in that direction. Thirdly, although presenting good results, most of the conclusions were drawn through simulations and there are very few experiments with robots in real scenarios. Finally, by presenting an innovative, cooperative and distributed method for patrolling infra-structures, it is also intended to deal with non-deterministic and unpredictability in the multi-robot patrolling task, as well as prove its feasibility in the real world. All these arguments serve as basis to propose a more advanced strategy for supervision and patrolling using a team of homogeneous mobile robots, endowed with an environment topological representation, without any centralized coordinator unit and using simple communication methods between them to cooperatively solve the problem.

Previously in this section, it was clarified why it is important to overcome weaknesses identified in precedent works and it was also shown how the proposed ideas represent an innovation in this context. In the next section, the work program is presented and more detail is given on how to approach these ideas to tackle the problem.
4.3 Work Program

The work plan for the approaching Ph.D. studies comprises a succession of steps. Initially, it is intended to implement a battery of simulations using mostly distributed state of the art multi-robot patrolling strategies with different team sizes, diverse topological environment dispositions and minimizing, at the same time, assumed simplification. Manifestly, this intensive simulation step must be carefully planned in advance in order to define the variables to measure, establish all the parameters and ensure the same conditions for every trial. After this first step, by means of data analysis, inductions on the scalable behavior of the team and primary conclusions will be drawn. Eventually, some simulations trials are additionally designed to confirm or reject any left assumption. After this iterative process, where simulations are run and data is analyzed until the behavior model of all variables is perceived, the development of the formal mathematical model, considering all variables, will take place. In this phase of the project, a great deal of knowledge on the ability of a mobile robot team to scale to larger teams sizes in patrolling missions is expected to be produced. To wrap up the study on scalability of these systems, another important contribution foreseen will be the development of the method for automatic estimation of the optimal team size according to a given optimization criterion. The idea behind this method is to produce a tool, which will assist investigators in this field to dimension their teams of robots in order to patrol a given environment, assuming some existing constraints. Possible optimization criteria may be based, for example, on minimum necessary average idleness of points in the environment, minimum individual productivity of each robot or even maximum distance travelled by each robot. After developing the method, the first stage of the studies finish.

Taking advantage of the study carried in the first stage, a new patrolling strategy is intended to be developed. This strategy will be designed as a cooperative, decentralized, flexible and scalable approach with efficient resource usage and simple communication mechanisms, where each agent has local reason abilities and autonomy, in order to achieve effective coordination and group performance. After proposing it, validation of the strategy will arrive firstly, by means of experimental simulations using a robotic platform like Player/Stage [Gerkey et al., 2003] or ROS [Quigley et al., 2009] and then by migrating to a real scenario using a team of mobile robots in an experimental model eventually built.
in the Mobile Robots Laboratory (MRL) of the Institute of Systems and Robotics (ISR) of Coimbra. In this stage, it is intended to prove the feasibility of the new strategy using a real scenario and its non-deterministic nature, overcoming the previously appointed weaknesses of works in this field.

After the experimental validation, the Ph.D. thesis will be written, which will contain an updated version of the extensive state of the art on multi-agent patrolling strategies presented in this document. Note that throughout the entire course of the work, articles reporting the progress of these studies are expected to be published both in international conference proceedings as well as in scientific journals. Figure 4.1 illustrates all steps of the work, in the form of a Gantt chart, and the expected time slots assigned to each task.

**Figure 4.1:** David Portugal’s Ph.D. Work Plan.

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<th>Task Description</th>
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<th>2011</th>
<th>2012</th>
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Chapter 5

Conclusions

In this Thesis Project, some introductory concepts have been presented to lay the groundwork for the prospected Ph.D. studies. Firstly, the context and motivation of the research and important characteristics of multi-robot systems were presented. Then, the multi-robot patrolling problem was defined and a great variety of strategies already presented on the literature to solve this problem as well as conclusions drawn in previous works were analyzed.

Also, important issues related to the problem, beyond the strategy, were addressed and discussed towards covering the problem in a more complete way. Finally, some important weaknesses were identified in preceding works, which led to present the methodology, new directions of research and innovative scientific contributions, exploring the context to overcome previous gaps and produce advanced knowledge in this field.

After this introductory research and planning phase, it is now time to proceed with the Ph.D. studies. During the course of the work, the student will be supported by the Portuguese government organization Foundation for Science and Technology (FCT), which conceded a Ph.D. grant with reference SFRH/BD/64426/2009.
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