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Decentralized Coverage Control Problems for Mobile Robotic Sensor and Actuator Networks

Andrey V. Savkin • Teddy M. Cheng • Zhiyu Xi
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PREFACE

Distributed coverage control problems for mobile robotic sensor and actuator networks have attracted considerable attention in recent years. The importance of the field of coverage control in robotic networks is quickly increasing due to the growing use of mobile robots and distributed wireless networks for sensing coverage and monitoring. The four most common types of coverage problems for mobile sensor networks are barrier coverage, sweep coverage, blanket coverage, and encircling coverage. These four types of coverage have numerous practical applications in monitoring and control of industrial and environmental processes. This book develops and studies distributed control algorithms for decentralized self-deployment of mobile robotic networks aiming to provide effective and efficient solutions of these types of coverage problems. Furthermore, for networks consisting of mobile robots that are equipped with both sensors and actuators, the problem of termination of moving environmental regions is introduced and studied.

The current book is primarily a research monograph that describes, in detail and in a unified framework, some of the latest developments on distributed coverage control problems for mobile robotic sensor and actuator networks. The intended audience of the book includes postgraduate students, researchers, and industry practitioners working in the areas of robotics, control engineering, communications, computer science, information theory, signal processing, and applied mathematics who have an interest in the emerging field of coverage control of mobile sensor/actuator networks.

This book is essentially self-contained. The reader is assumed to be competent in basic undergraduate level mathematical techniques. The theory and algorithms of distributed coverage control for mobile sensor and actuator networks are discussed in detail and illustrated by numerous examples. So a reader familiar with basic numerical methods and linear algebra will be able to understand both the algorithms presented and their mathematical analysis, as well as to implement the coverage algorithms directly from the book. The developed coverage control algorithms are fully decentralized, computationally efficient, and easily implementable in engineering practice. Furthermore, this book presents detailed mathematical studies of the proposed distributed coverage strategies.

The content of this book derives from a period of collaboration between the coauthors from 2009 to 2014. Some of the presented results have appeared in isolation in journal and conference papers. The manuscript integrates them with many new authors' original results and presents the entire material in a systematic and coherent fashion.

This book is one of the first research monographs in the diverse and challenging area of mobile robotic sensor and actuator networks. We hope that the reader finds this work both useful and interesting and is inspired to explore further the emerging field of distributed coverage control problems.

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CHAPTER 1

INTRODUCTION

1.1 Distributed Coverage Control of Mobile Sensor and Actuator Networks

Sensing coverage is an important issue in the field of sensor networks. For wireless sensor networks, it is considered to be a measure of their quality of service; see, e.g., [13, 32, 64, 129] and references therein. Due to the rapid development of communication and microelectronics technologies, it became possible to employ spatially distributed wireless sensor networks for performing tasks like target tracking, hazardous environment monitoring, and border surveillance in a geographically vast area. To ameliorate the performance of coverage by such a network, the sensors should be placed at proper, ideally optimal, locations. However, for a large-scale network, it would be a daunting and expensive task. To improve coverage and reduce the cost of deployment, employing movement-assisted or mobile sensors is an attractive option; see, e.g., [15, 66, 114, 122, 124]. A network of such sensors is typically implemented by deploying a group of mobile sensor equipped robots, where each robot can be viewed as a mobile sensing node. The robots can be unmanned autonomous terrain, underwater, or aerial vehicles. Their sensing capabilities are utilized to sense and monitor a spatial area of interest.

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Three types of coverage problems for mobile wireless sensor networks are defined in the seminal paper by Gage [35], namely:

1. *Barrier coverage*: to achieve a static arrangement of nodes that minimizes the probability of undetected intrusion through the barrier,

2. *Sweep coverage*: to move a number of nodes across a sensing field so that it addresses a specified balance between maximizing the detection rate of events and minimizing the number of missed detections per unit area,

3. *Blanket coverage*: to achieve a static arrangement of nodes that maximizes the detection rate of targets appearing in the sensing field.

In barrier coverage, a sensing barrier is formed by an array of sensing nodes so that any intrusion through the barrier is detected [19, 58, 59, 65, 112, 125]. Sweep coverage is achieved by moving a number of sensing nodes across a sensed field to search for and detect targets in the field [12, 26, 38, 133]. Finally, the purpose of blanket coverage is to monitor a given area so that targets appearing in this area are detected by the network of sensing nodes [29, 42, 122, 124, 137].

Practical applications of the described three types of coverage in mobile robotic sensor networks include minesweeping [12], border patrolling [59], environmental studies, detecting and localizing the sources of hazardous chemicals leakage or vapour emission, detecting sources of pollutants and plumes, environmental monitoring of disposal sites on the deep ocean floor [54], sea floor surveying for hydrocarbon exploration [9], ballistic missile tracking, bush fire monitoring, oil spill detection at high seas, environmental extremum seeking [28, 78, 137], environmental field level tracking [79], target capturing [132], and many others.

In order to achieve objectives in these coverage problems, each sensor in a network should cooperate with other sensors to fulfil a common goal. The cooperation takes place in the form of coordinated control of the sensors movement using the information from the network. However, to reduce the cost of operation, each sensor may have very limited resources, e.g., communication, sensing, or computing powers, and may suffer from severe detection and communication constraints. Therefore, the use of a centralized control algorithm is not a practical approach since not the entire global information is available to each sensor. To compensate for the lack of global information and centralized controllers, decentralized and distributed approach should be considered.

Broadly speaking, distributed control of self-deploying mobile robotic sensors falls within the general area of decentralized control, but the unique aspect of it is that mobile robotic sensors are dynamically decoupled; i.e., the motion of any sensor does not directly affect the other sensors. The study of decentralized control for groups of autonomous vehicles or robots has emerged as a challenging research area in the last decade; see, e.g., [7,39,45,48,52,53,69,85,89,92,96,105,113,115,127]. Distributed control laws for such groups of mobile robots are indeed motion coordination rules that rely only on a local information. In this control framework, each mobile robot is driven on the basis of information about coordinates or velocities of only a few other robots, typically its currently closest neighbors. To develop such local control rules, researchers in this new emerging area of engineering are finding much inspiration from the field of biology, where the problem of animal aggregation is central in both ecological and evolutionary theory. Animal aggregations, such as schools of fish, flocks of birds, or swarms of bees, are believed to use simple, local motion coordination rules at the individual level, which at the same time result in remarkably complex intelligent behaviors at the group level; see, e.g., [6, 34, 84, 111, 126].

To explain and simulate these behaviors, Vicsek *et al.* [120] proposed a simple discrete-time model of a system of several autonomous agents, where each agent's motion is updated using a local rule based on its own state and the states of its "neighbors". This simple but interesting model was then analytically studied by a number of researchers, e.g., [53, 55, 92, 96, 131, 135]. Moreover, modifications of the Vicsek model have also been carried out in, e.g., [55, 62, 63, 135]. For example, a Vicsek-type model with adaptive velocities is proposed in [62, 63], whereas a heterogeneous sensing Vicsek model is introduced in [130]. In addition, the converging rate of the Vicsek model is studied in [55, 135]. Also, the Vicsek model can be viewed as a special case of the model proposed in [93] for the computer animation industry to mimic animal aggregation.

To develop such local motion coordination rules, approaches like information consensus [53, 92, 96, 131] or potential field [90] are typically adopted. For low-power mobile sensor networks, consensus-based algorithms are especially attractive since they are relatively simple and require low computational cost.

Another topic of this book is study of mobile robotic sensor and actuator networks. They consist of nodes that are mobile robots (ground, underwater, or aerial unmanned vehicles). Some of these nodes are sensors and some are actuators (also called actors), whereas some nodes are endowed with both sensing and actuating capacities. Actuating capabilities are utilized to dispense control signals with the goal of achieving certain control objectives. Many modern engineering applications include the use of such networks to provide efficient and effective monitoring and control of industrial and environmental processes. These networks are able to achieve improved performance, along with reduction in power consumption and production cost. Theoretical research on mobile robotic sensors/actuator networks is at an early stage; however, some interesting theoretical results can be found in [14, 31] and references therein.

The emerging area of mobile robotic sensor and actuator networks lies at the crossroad of robotics, control engineering, computer science, and communications. The importance of this field is quickly increasing due to the growing use of wireless communications and mobile robots.

This book studies various coverage control problems for mobile sensor networks including barrier, sweep, and blanket coverage problems. Moreover, a new type of coverage referred to as encircling coverage is introduced. For mobile robotic sensor and actuator networks, the problem of termination of a moving two-dimensional region is introduced and studied. The proposed coverage control algorithms are based on the consensus approach, which was studied by many researchers in the last decade. All the robotic sensor and actuator motion algorithms developed in the book are fully decentralized and distributed, computationally efficient, easily implementable in engineering practice, and based only on information about the closest neighbors of each mobile node and local information about the environment. Moreover, the nodes have no prior information about the environment in which they operate.

It should be pointed out that this book is problem oriented, with each chapter discussing in detail distributed coverage problems and solutions that arise in the rapidly emerging area of mobile robotic sensor and actuator networks. The goal of this monograph is to present a computationally efficient, reliable, distributed, and easily implementable framework for coverage control of mobile robotic sensor and actuator networks, so that the ultimate goal of their applications (environmental or industrial monitoring, target detection and following, border protection and many others) can be fulfilled. Such a framework is very important because it is expected that future mobile wireless sensor and actuator networks will be more complex, heterogeneous, and vastly distributed. They may execute multiple tasks and consist of millions of mobile nodes.

1.2 Overview of the Book

In this section, we briefly describe the results presented in this research monograph.

Chapter 2 introduces the concept of barrier coverage and considers the problem of distributed barrier coverage between two landmarks or points. A distributed self-deployment algorithm is proposed. Moreover, we give a mathematically rigorous proof of its convergence and verify its performance by computer simulations. As always in this book, decentralized control algorithms are developed using the consensus approach, and they require only local information on the closest neighbors of each mobile robotic sensor. In this chapter, we introduce the standard Main Connectivity Assumption on the communication graph sequence of a mobile sensor network, which was first introduced in [53]. This assumption will also be used in the main results of Chapters 4, 5, 6, 7, and 8.

Chapter 3 addresses a problem of multi-level barrier coverage. The proposed distributed and decentralized control law drives a network of sensors to form K layers of parallel sensor arrays between two given points. The advantage of this law is that it is computationally efficient and easily implementable. Moreover, the sensors have no prior information about the region where the coverage is required. The main result of this chapter assumes connectivity of the communication graph of the mobile sensor network at any time, and this assumption is stronger than the Main Connectivity Assumption from Chapter 2. The main results of Chapters 9 and 10 are also based on this stronger connectivity assumption.

In Chapter 4, we theoretically develop decentralized control laws for the coordination of a mobile robotic sensor network to address the barrier and sweep coverage problems in corridor environments. The proposed control algorithms are applicable to real-time coverage operations. The control algorithms are illustrated by numerical simulations. Even though the theoretical results on the developed control algorithms are proved for straight corridors, computer simulations demonstrate that the algorithms are effective in curved corridors as well.

Chapter 5 develops a set of decentralized algorithms for the coordination of a mobile robotic sensor network to address a problem of sweep coverage along a given line. Again, the control laws are based on some consensus algorithms that are computationally efficient and easily implementable. To achieve sweep coverage, the control law drives the network of robotic mobile sensors to form a sensor barrier that moves perpendicularly to the path at a given speed. Also, the separation between each pair of the robots in the sensor barrier can be adjusted. Numerical simulations are presented for a number of scenarios to illustrate the proposed distributed algorithm. To show its practical applicability, we provide computer simulation results for an illustrative example of a sea exploration operation with multiple vessels.

Chapter 6 considers the blanket coverage problem, which is believed to be more difficult than barrier and sweep coverage problems. We propose a distributed motion coordination algorithm for a mobile sensor network to address a blanket coverage problem. Unlike the algorithms of the previous chapters, the proposed blanket coverage algorithm is randomized and has a highly probabilistic nature. According to this algorithm, the sensors are deployed on vertices of a regular triangular grid. We derive some asymptotic optimality of such grids from the classical mathematical result of Kershner [56]. We also prove convergence with probability 1 of this randomized algorithm for an arbitrary bounded region, which may be unknown to the robotic sensors a priori.

In Chapter 7, we modify the decentralized randomized control algorithm of Chapter 6 to navigate a network of autonomous mobile robotic sensors so that they collectively form a desired geometric pattern on a square grid starting from any initial deployment. In particular, we consider self-deployment with desired shapes such as interiors of a circle, an ellipse, a rectangle, a ring, and a regular hexagon. We also propose a randomized algorithm for self-deployment of a robotic sensor network in an unknown bounded region with obstacles. For the proposed distributed randomized algorithms, convergence with probability 1 is proved.

Chapter 8 introduces the problems of encircling coverage and region termination for a moving and deforming planar region and a network of mobile sensors/actuators. We propose a distributed randomized algorithm for these problems. Asymptotic optimality and convergence with probability 1 of the proposed algorithm are proved in the case of an arbitrary bounded region, which may be unknown to the mobile sensors/actuators a priori. The algorithm is decentralized, computationally efficient, and based only on information on the closest neighbors of each mobile sensor and the distance to the planar region. It should be pointed out that our algorithm for encircling and termination of a moving region is partially inspired by the famous Hannibal double-envelopment maneuver during the Battle of Cannae in which the army of Carthage under Hannibal decisively defeated a numerically superior army of the Roman Republic in 216 BC; see, e.g., [43]. Illustrative examples show that the proposed algorithm encircles and terminates moving regions in a pattern similar to encirclement and annihilation of the Roman army by the Carthaginians.

Chapter 9 addresses the blanket coverage problem that is slightly different from the blanket coverage problem studied in Chapter 6. We develop a decentralized control law that, starting from any initial deployment of the sensors, drives them to form a sensor lattice that fully covers a given two-dimensional region between two boundaries. The nodes of this lattice are in triangular pattern, which not only provides 1-coverage but also 6-connectivity. As in Chapter 6, we prove, by using the Kershner theorem, that this pattern is asymptotically optimal in terms of the minimum number of sensors required to fully cover the region. As always in this book, the proposed control law is based on the consensus algorithm approach, computationally efficient and easily implementable in practice. The control algorithm is distributed, and the control action of each sensor is based on the local information of its neighboring sensors. Moreover, the mobile sensors have no prior information about the region to be covered. It should be remarked that the blanket coverage algorithm of this chapter is totally different from the algorithm of Chapter 6. The approach of Chapter 9 is deterministic and close in spirit to the ideas of Chapters 2–5, whereas the algorithm of Chapter 6 is randomized. A number of numerical simulations is presented for different types of boundaries to illustrate the proposed algorithm.

Chapter 10 offers a decentralized formation control algorithm to coordinate a network of mobile robotic sensors so that they collectively move into a rectangular lattice pattern from any initial deployment. Numerical simulations are presented to illustrate this algorithm. Unlike blanket coverage type algorithms of Chapters 5–9 under which the sensors are eventually deployed in steady formations, the distributed algorithm of Chapter 10 ensures that the mobile robotic sensors move as a swarm with a desired geometric shape in a common direction with a common speed.

1.3 Some Other Remarks

The chapters of this book can be divided into two groups. In Chapters 2–5, 9, and 10, we propose distributed coverage algorithms that are based on building a one-dimensional structure of mobile sensors and then driving this structure to solve a barrier, sweep, or blanket coverage problem. On the other hand, Chapters 6-8 introduce a totally different class of distributed control algorithms that are based on finding consensus on a certain regular two-dimensional grid and then finding a suitable location for each mobile node on one of vertices of this grid using a randomized algorithm. Moreover, all the algorithms of Chapters 2–5, 9, and 10 are deterministic, whereas all the algorithms of Chapters 6–8 are randomized.

It should be pointed out that the mobile robotic sensor and actuator networks guided by the distributed control algorithms developed in this book can be naturally viewed as networked control systems; see, e.g., [72,74,97,98] and references therein.

Some local-rules-based intelligent behavior is expected from very large scale robotic systems. The term "very large scale robotic system" is introduced in [90] for systems consisting of autonomous robots numbering from hundreds to tens of thousands or even more. Because of decreasing costs of robots, interest in very large scale robotic systems is growing rapidly. Possible applications include underwater exploration, military surveillance, and many others. In such multi-robot systems, robots should exhibit some forms of cooperative behavior. The research presented in