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Decentralized identification and control of networks of coupled mobile platforms through adaptive synchronization of chaos

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HIGHLIGHTS

- Adaptive strategy to detect variations of network topology.
- Estimation of connectivity links.
- Synchronization of chaotic oscillators.
- Decentralized controller to maintain a desired network formation.
- A novel chaotic synchronization based formation control algorithm.

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ABSTRACT

In this paper, we propose an application of adaptive synchronization of chaos to detect changes in the topology of a mobile robotic network. We assume that the network may evolve in time due to the relative motion of the mobile robots and due to unknown environmental conditions, such as the presence of obstacles in the environment. We consider that each robotic agent is equipped with a chaotic oscillator whose state is propagated to the other robots through wireless communication, with the goal of synchronizing the oscillators. We introduce an adaptive strategy that each agent independently implements to: (i) estimate the net coupling of all the oscillators in its neighborhood and (ii) synchronize the state of the oscillators onto the same time evolution. We show that, by using this strategy, synchronization can be attained and changes in the network topology can be detected. We further consider the possibility of using this information to control the mobile network. We apply our technique to the problem of maintaining a formation between a set of mobile platforms which operate in an inhomogeneous and uncertain environment. We discuss the importance of using chaotic oscillators, and validate our methodology by numerical simulations.

1. Introduction

In the last decade, the coordination of networked multi-agent systems has been intensively investigated. Both the robotic and communication research communities have been working on how to properly integrate wireless communication in motion planning algorithms, considering the random properties of the RF channels and the mobility of the autonomous agents. A typical goal of the research in this area is to accomplish a certain mission while maintaining connectivity of the network. In any real application, the network topology may change in time due to the random nature of the communication channel and the complexity of the environment. For example, an agent may remain isolated and become unable to accomplish the mission, or unwanted disconnections may occur due to the presence of obstacles. Moreover, maintaining connectivity becomes even more challenging when the network architecture is decentralized, for example when each agent has access only to local information about its connections and the surrounding environment.

Advances in sensor technology in the last three decades have helped accelerate interest in the field of robotics. As robots become smaller, more capable, and less expensive, there is a growing demand for teams of robots in various application domains. Multi-agent robotic systems are particularly well suited to execute tasks that cover wide geographic ranges and/or depend on

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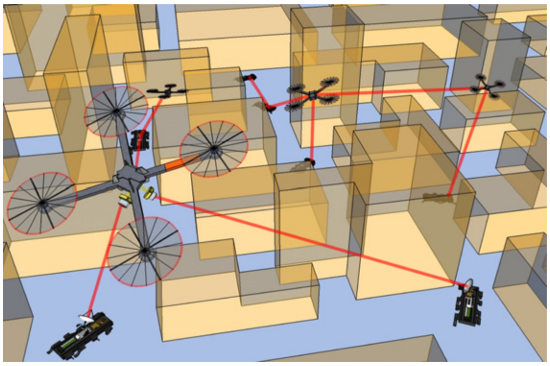

Fig. 1. A heterogeneous network of coupled robotic platforms operating in a cluttered virtual environment. The lines between the robots represent line-of-sight communication paths.

capabilities that are varied in both quantity and difficulty. Example applications include exploration and surveillance [1], health monitoring [2], autonomous transportation systems [3], nano-assembly [4] (*i.e.,* the programming and coordination of a large number of nanorobots), and hazardous waste clean-up [5]. More recently, research in multi-agent robotic systems has focused on robot swarms. Robot swarms are composed of large numbers of robots capable of covering wide regions and performing tasks that require significant parallelization and robustness, such as parts inspection [6], warehouse automation [7], and environmental monitoring [8].

Fig. 1 shows a pictorial representation of the situation envisioned in this paper, in which a heterogeneous robotic network operating in a cluttered environment maintains line-of-sight communication between aerial and ground robots, by using light pulses (*e.g.,* lasers transmitters and receivers [9,10]). Note that communication is selective: only those robots whose line-of-sight communication paths are not crossed by obstacles are coupled. Also, the network is time varying, as connections can be dynamically created or disrupted as the agents move in different areas of the environment. Our underlying assumptions are the following: (i) the robots move in an unknown environment while trying to accomplish a coordinated mission, (ii) they operate in a context characterized by limited availability of information, and (iii) they have no *a priori* knowledge of the topology of the network, and need to estimate it throughout the mission.

Previous work [11–14] has shown the possibility of using adaptive synchronization of chaotic systems in a sensor network application, for which the sensors are static. In this paper, we extend this approach to the case that the oscillators are placed on mobile platforms that move in an unknown, inhomogeneous, and time-varying environment. For this case, we consider that the strengths of the couplings may be affected by the relative motion of the platforms, as well as by the influence of external factors, such as the presence of obstacles in the environment.

We propose that each mobile robot is equipped with a chaotic oscillator whose state is propagated to the others by wireless communication. At each time, the signal received by each platform is the aggregate chaotic signal broadcast by all the oscillators with which it communicates. Given this available information, we devise a decentralized adaptive strategy that each agent independently implements in order to reach and maintain synchronization while estimating changes in the local connectivity of the network, such as deletion and aggregation of connections.

Moreover, we question how such information can be used to control the network. For example, in many practical applications, an important goal is that of maintaining network connectivity, while avoiding collisions between the platforms [15,16]. In what follows, we show that a novel chaos synchronization based formation control algorithm can be effective in maintaining desired distance and bearing coordinates between a set of mobile robots.

1.1. Related work

Multiple mobile robotic systems and wireless communications have been extensively studied for several years. Recently, roboticists have recognized the need to consider realistic communication models when designing multi-robot systems [17–21]. For instance, the authors of [18] formally analyze the properties of the communication channel and use them to optimally navigate autonomous agents to improve the communication performance in terms of signal-to-noise ratio and bit error rate. In [19], the authors propose a modified traveling salesperson problem to navigate an underwater vehicle in a sensor field, using a realistic model that considers acoustic communication fading effects. In [21], a set of algorithms is presented to repair connectivity within a network of mobile routers, and then show outdoor experimental results to validate their algorithms, while in [22] an agent attempts to estimate the network topology by using only local information.

In [17], a chain of mobile routers is used to keep line-of-sight communication between a base station and a user that moves in a concave environment. In [23], the authors optimize routing probabilities to ensure desired communication rates while using a distributed hybrid approach. In [24], the authors analyze connectivity in consensus networks with dynamical links, while Ref. [21] presents a set of algorithms to repair connectivity within a network of mobile routers.

Similar to the work presented in this paper, [25] investigates the problem of how to estimate the connection topology in complex dynamical networks by means of a steady-state control based identification method. In [26], the authors propose an algorithm inspired by Kirchhoff's laws in electrical circuits, to detect losses (also called "cuts") in the connectivity of large sensor networks. The same problem is also investigated in [27], in which a subset of sensors, called "sentinels", communicates on a regular basis to a base station. The authors show that the base station is able to estimate the network topology based only on detections of communication failures with the sentinel nodes.

In a different context, a large literature has investigated synchronization of networks of coupled dynamical systems, see e.g., [28–31]. Refs. [11,32] present an adaptive technique to synchronize a large sensor network in which each static node receives an aggregate signal from the other nodes in the network. This strategy has been tested in an experimental network of coupled opto-electronic systems in [13,14]. A different strategy, aimed at estimating communication delays, was proposed in [33].

In our work, we consider an extension of the strategy in [11,32], and we show that a similar approach can be used to detect changes in networks of coupled mobile robotic platforms. In practical applications, it is often the case that the robots operate in a cluttered unknown environment and in a decentralized fashion; moreover, the connectivity may be unavailable. In what follows, we will address such situations by introducing a decentralized adaptive technique, which will be proven useful to estimate and track the time evolution of the network topology.

The remainder of this paper is organized as follows. In Section 2, we give some preliminary graph-theoretical definitions that will be used throughout the paper. In Section 3, we introduce the model for the robot dynamics, the communication connectivity strategy, and the sensing strategy based on the chaotic oscillators. In Section 4, we present the adaptive strategy that incorporates the chaotic oscillators, followed by extensive simulation results in Section 5. In Section 6, we discuss the usefulness of dealing with