

POTENTIAL FIELD-BASED DECENTRALIZED CONTROL METHODS FOR  
NETWORK CONNECTIVITY MAINTENANCE

By  
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To my wife Yang Chen, my mother Baozhi Hu, and my father Heping Kan, for their  
unwavering support and constant encouragement

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In cooperative control for a multi-agent system, agents coordinate and communicate to achieve a collective goal (e.g., flocking, consensus, or pattern formation). As agents move to perform a desired mission objective, ensuring the group remains close enough to maintain wireless communication (i.e., the group does not partition) is a great challenge in a decentralized control manner. The use of an artificial potential field is one approach that has been widely used in path planning for multi-agent systems, where an attractive potential is used to model the control objective and a repulsive potential is used to prevent collisions among the agents and obstacles. The focus of this dissertation is to develop potential field based decentralized controllers for a group of agents with limited sensing and communication capabilities to perform required mission objectives while preserving network connectivity.

A two level control framework is developed in Chapter 2 for connectivity maintenance and cooperation of a multi-agent system. All agents are categorized as clusterheads or regular nodes. A high level graph is composed of all clusterheads while a low level graph is composed of all regular nodes. Artificial potential field based controllers are then developed to maintain existing links connected in both low and high level graphs and ensure that a group of agents switch from one connected configuration to another without disconnecting the underlying network in process.

In Chapter 3, based on the navigation function formalism, a decentralized control method is designed to enable a group of agents to achieve a desired global configuration from a given connected initial graph with desired neighborhood between agents, while maintaining global network connectivity and avoiding obstacles, using only local feedback and no radio communication between the agents for navigation. The initial graph assumption in Chapter 3 is then eliminated in Chapter 4, where a novel strategy using a prefix labeling and routing algorithm and a navigation function based control scheme is developed to achieve a desired formation for a group of identical agents from an arbitrarily connected initial graph.

A group of mobile robots with nonholonomic constraints are considered in Chapter 5. A decentralized continuous time-varying controller based on a modified dipolar navigation function is developed to reposition and reorient those mobile robots with nonholonomic constraints to a common setpoint with a desired orientation while maintaining network connectivity during the evolution, using only local sensing feedback from its one-hop neighbors.

The work in Chapter 6 applies the control techniques developed in engineering to investigate and influence emotions of people in a social network, where a distributed controller for each individual is designed to achieve emotion synchronization for a group of individuals in a social network (i.e., an agreement on the emotion states of all individuals). Motivated by the non-local property of fractional-order systems, the emotional response of individuals in the network are modeled by fractional-order dynamics whose states depend on influences from social bonds. Encoding the control objective of emotion synchronization and modeling the maintenance of social bonds as a constraint, a potential function is developed to ensure asymptotic convergence of each emotion state to the common equilibrium in the social network.

Chapter 7 concludes the dissertation by summarizing the work and discussing some remaining open problems that required further investigation.

# CHAPTER 1 INTRODUCTION

## 1.1 Motivation

Multi-agent systems under cooperative control provide versatile platforms that have the potential to be used in various commercial and military applications. For instance, a list of “some of the main applications for cooperative control of multi-vehicle systems” is provided in [2], which includes:

- Military Systems: Formation Flight, Cooperative Classification and Surveillance, Cooperative Attack and Rendezvous, and Mixed Initiative Systems;
- Mobile Sensor Networks: Environmental Sampling and Distributed Aperture Observing;
- Transportation Systems: Intelligent Highways and Air Traffic Control.

These types of tasks usually require or can benefit from collaborative motion of a group of agents, and thus the agents must be able to exchange information over some form of communications network. For most applications, communications will be over a wireless network, in which the communication links between agents are dependent on the propagation of electromagnetic signals between the agents, and the electromagnetic power density decreases with distance. However, when performing desired tasks, the underlying network connectivity can be impacted due to the motion of agents. If the network is partitioned, the agents can no longer coordinate their movements, and the mission may fail. Hence, control algorithms must be designed in a cooperative manner to preserve network connectivity when performing desired tasks.

Some applications can adopt a centralized control approach where one algorithm determines and communicates the next required movement for each agent. For some applications, the centralized approach is not practical due to the potential for compromised communication with or demise/corruption of the central controller. Decentralized control is an alternative approach in which each agent makes an independent decision based on

either global information communicated through the network or local information from one-hop neighbors. Methods that use global information require each agent to determine the relative trajectory of all other agents at all time by propagating information through the network, resulting in delays in the trajectory information and consumption of network bandwidth, effects that limit the network size. Methods that use local information need only relative trajectories of neighboring agents; however, difficulties arising from performing required mission objectives for the global network using local feedback can cause the network to partition. When the network partitions, communication between groups of agents can be permanently severed leading to mission failure.

Given the wide application of multi-agent systems and the desire to maintain network connectivity in a decentralized manner, this dissertation is motivated by the following questions:

1. How can a decentralized control strategy be designed to ensure global network connectivity using only local available information?
2. How can the required collective mission objective be achieved in a cooperative way while preserving network connectivity?
3. Is it possible to extend the models and methods developed for multi-agent systems in engineering be leveraged to yield insight to influence social groups?

## **1.2 Problem Statement**

Accomplishing desired collective mission objectives for a networked multi-agent system highly depends on the coordination of their actions and the peer-to-peer, wireless communication among agents. In this dissertation, limited communication and sensing capabilities for each agent are considered, that is two agents can communicate and exchange information if they are within a specified maximum communication range and cannot communicate if they are outside of that range. Hence, ensuring that the overall network remains connected requires the specified agents stay within predetermined sensing and communication ranges, and the cooperative objectives must be accomplished by using

local information obtained from the limited sensing and communication abilities of each agent. The work presented in this dissertation examines decentralized control methods for networked multi-agent systems to achieve global collective objectives, such as formation control and consensus, while preserving connectivity of the global network using local information from immediate neighbors.

### 1.3 Literature Review

This section provides a review of relevant literature for each chapter.

**Maintenance of network connectivity for a multi-agent system:** Motivated by the practical need to keep agents in a single group, recent results such as [3–11] are focused on the network connectivity maintenance problem based on the construction of an artificial potential field. Artificial potential fields have been widely used in path planning for multi-agent systems, where an attractive potential is used to model the control objective and a repulsive potential is used to prevent collisions among the agents and obstacles [12, 13]. In [3] and [10], a potential field based centralized control approach is developed to ensure the connectivity of a group of agents using the graph Laplacian matrix. However, global information of the underlying graph is required to compute the graph Laplacian. In [4], connectivity maintenance is performed in the discrete space of graphs to verify link deletions with respect to connectivity, and motion control is performed in the continuous configuration space using a potential field. In [5], a potential field-based neighbor control law is designed to achieve velocity alignment and network connectivity among different topologies. In [6] and [8], a repulsive potential is used for a collision avoidance objective, and an attractive potential field is used to drive agents together. Distributed control laws are investigated to ensure edge maintenance in [11] by allowing unbounded potential force whenever pairs of agents are about to break the existing links.

To ensure network connectivity during the mission, a two level control strategy is developed for a multi-agent system in Chapter 2, where all agents are categorized as

clusterheads or regular nodes. A high level graph is composed of all clusterheads and the motion of the clusterheads is controlled to maintain existing connections among them. A low level graph composed of all regular nodes is controlled to maintain connectivity with respect its specific clusterhead. Artificial potential field based controllers are then developed in Chapter 2 to maintain the existing links connected in both low and high level graphs all the time and to ensure that a group of agents switch from one connected configuration to another without disconnecting the network.

### **Formation control with network connectivity for a multi-agent system:**

Typical approaches in formation control include leader-follower [14, 15], behavioral-based [16, 17], virtual structures [18, 19] and graph-theory-based [10, 20–25] methods, to name a few. However, no constraints on the availability of other agents’ states and information about the environment are considered: network connectivity is not taken into account in such results. When considering network connectivity, overviews of techniques for formation control are given in [2, 26, 27]. The earliest works on formation control with network connectivity are discussed in [26] with a focus on the impact of a given network connectivity on the stability and controllability of formations of robots without considering the control required to ensure network connectivity during the mission. Although some results described in [2, 27] are focused on maintaining network connectivity during formation control, an open problem remains in developing design a decentralized control approach for a group of agents seeking a desired formation in an uncertain environment while preserving network connectivity.

One of the most widely used approaches in formation control is to use artificial potential fields to guide the movement of the agents. A common problem with artificial potential field-based control algorithms is the existence of local minima when attractive and repulsive force are combined [28]. In Chapter 2, network connectivity is ensured by using an artificial potential field-based controller; however, the agents have the potential to be trapped by local minima. A specific type of artificial potential, called a navigation

function, achieves a unique minimum (c.f., [29–31]) and has been widely used in motion control for multi-agent systems (see e.g., [4, 32–35]). The navigation function developed in [30] is a real-valued function that is designed so that the negated gradient field does not have a local minima. The negated gradient of the navigation function is attracted towards the goal and repulsed by obstacles for almost all initial states. As such, closed-loop navigation function approaches guarantee convergence to a desired destination. The navigation function framework is extended to multi-agent systems for obstacle avoidance in results such as [28, 34, 36–38]; however, agents within these results acted independently and were not required to achieve a network objective. In contrast, results in [39–41] use potential fields/navigation functions to achieve obstacle avoidance while the agents are also required to achieve a cooperative network objective (e.g., formation control or consensus); however, these results assume the agents can always communicate (i.e., the graph nodes are assumed to remain connected). The assumption of a connected graph is restrictive for a mobile network, where communication depends on the distance between agents, which can also be a function of the environment and available transmitting power. In [9], a potential field is designed for a group of mobile agents to perform desired tasks while maintaining network connectivity. It is unclear how the potential field method in [9] can be extended to include static obstacles, since the resulting closed-loop dynamics can not be expressed as a Metzler matrix with zero sums as required in the analysis in [9]. Moreover, the work in [9] only proves that all states converge to a common value that can be influenced by the initial states [42].

Motivated to avoid local minima when using artificial potential field-based approach, a navigation function based decentralized controller is developed in Chapter 3 to ensure network connectivity and stabilize a group of agents in a required formation from a connected initial graph (agents are considered as nodes on a graph) with a desired neighborhood, while avoiding collisions with other agents and external obstacles.

### Formation control with network connectivity from an arbitrary initial

**graph:** The result in Chapter 3 requires that the initial graph is connected in a desired way so that no initial communication link is allowed to be broken during the motion. Similar constraints on the initial graph connections are also presented in works such as [9] and [35]. However, assumptions on the initial graph can be limiting, since some applications may require agents to achieve desired formations from an arbitrary initial graph or dynamically change the achieved formations to adapt to the uncertain environment. For example, certain formations have proven to be particularly advantageous for efficiency of data gathering, data processing, and forecasting (cf., [43, 44]). Since the initial topology or the topology from the previous task may not be conducive to the current task, achieving a desired formation or transforming from one topology to another for a group of agents with limited knowledge is a challenging task. Hence, maintaining the overall network connectivity is paramount, and stabilizing a multi-agent system at a desired formation from an arbitrary initial topology using local feedback can be challenging.

In Chapter 4, each agent possesses only limited knowledge (i.e., limited sensing capabilities or knowledge about the environment and limited communication capabilities with nearby agents) to perform tasks such as formation control in a cooperative manner, where agents are required to coordinate their motion with respect to other agents. Limited sensing capabilities by agents in a network has been examined in results such as [39, 41, 45–47]. In [45], assuming that each agent is aware of its own destination, a group of mobile agents with limited sensing range is controlled to achieve desired formations based on a potential-field based approach in a non-cooperative way, where agents are not required to coordinate their motion with respect to other agents to achieve the desired formation. The result in [45] is extended to perform formation tracking in a cooperative way in [46], where limited sensing is used for collision avoidance only. A centralized leader-follower approach is developed to perform formation tracking in [47], and a centralized navigation function-based control strategy is developed in [39] to steer a group of mobile

agents with limited sensing capabilities to achieve a desired formation. Motivated by the need to maintain network connectivity, an artificial potential field-based decentralized method is used to prevent the network from partitioning and stabilize a group of agents with limited communication and sensing capabilities in a desired formation in [9, 11, 48], where the network connectivity is guaranteed by maintaining the initially established neighborhood all the time during the operation. However, a common assumption in the results of [9, 11, 48] is that the initial topology is required to be a supergraph of the desired topology ensuring the agents are originally in a feasible interconnected state. Such results may not be applicable to the applications which require a multi-agent system to start from an arbitrary connected initial graph or dynamically change the achieved formations to adapt to the uncertain environment, since the reorganization of the initial topology to a desired one may require the breakage of some prespecified neighborhood and results in the partition of the underlying network connectivity.

Contrary to the work of [9, 39, 41, 45–48], formation control for a group of agents with limited sensing and communication capabilities are considered in Chapter 4, in which the agents are identical and can take any position in the final topology. Based on the concepts of prefix labeling and prefix routing in [49–51], a novel network topology labeling algorithm developed in our previous work [52] is modified to dynamically specify the neighborhood of each agent in the initial graph according to the desired formation, and determine the required movement for all nodes to achieve the desired formation. By modeling network connectivity as an artificial obstacle, a navigation function based control scheme is developed in Chapter 4 to guarantee network connectivity by maintaining the neighborhood among agents determined by the prefix labeling algorithm, and ensure the convergence of all agents to the desired configuration with collision avoidance among agents using local information (i.e., local sensing and communication). An information flow is then proposed from the work of [53] and [54] to specify the required movement for extra agents to their destination nodes. The information flow-based approach generally

provides a path with more freedom for the motion of extra nodes without partitioning the network connectivity and allows communication links to be formed or broken in a smooth manner without introducing discontinuity. Convergence is proven using Rantzer’s Dual Lyapunov Theorem [55].

**Rendezvous of wheeled mobile robots with network connectivity:** Results such as [3–11] are developed to maintain the network connectivity in the application of formation control, flocking, consensus and other tasks in either centralized or decentralized manner. However, one common feature in most of the aforementioned work is that only linear models of motion are taken into account, i.e., the first order integrator. Although control design for the stabilization of a single robot with nonholonomic constraints has been extensively studied in the past decades [56, 57], such controllers may not be applicable for a networked multi-robot system with a cooperative objective, e.g., maintaining network connectivity. Motivated to navigate a system with nonholonomic constraints to a destination with a desired orientation, a dipolar navigation function was proposed and a discontinuous time-invariant controller was developed to navigate a single robot in [58]. The work in [58] was then extended to a multi-robot system with both holonomic and nonholonomic constraints in [36] and extended to navigate a nonholonomic system in three dimensions in [59]. However, only a time-invariant discontinuous controller was developed in [36, 58, 59]. In [8], when considering maintenance of the network connectivity, based on the work of [58], a discontinuous controller was used to steer a multi-robot system with nonholonomic constraints to rendezvous at a common position. However, each robot can only achieve the destination with arbitrary orientation and has to reorient at the destination. Moreover, the multi-robot system can only converge to a destination which depends on the initial deployment in [8]. Based on our previous work in [60], a decentralized continuous time-varying controller, using only local sensing feedback from its one-hop neighbors, is designed in Chapter 5 to stabilize a group of wheeled mobile robots with

nonholonomic constraints at a specified common setpoint with a desired orientation, while maintaining network connectivity during network regulation.

**Consensus of human emotion in a social network:** Social interactions influence our thoughts and actions through social networks which provide a means for more rapid, convenient, and widespread communication. For instance, flash mobs are being organized through social media for events ranging from entertaining public spontaneity to vandalism, violence, and crime [61–63]. Recent riots and protests [64–67] and ultimately revolution [68, 69], have been facilitated through social media technologies such as Facebook, Twitter, You Tube, and BlackBerry Messaging (BBM). In attempts to prevent, mitigate, or prosecute the sources of such social unrest, governments and law enforcement agencies are placing a greater emphasis on examining (and ultimately controlling) the structure of social networks. Scotland Yard is looking to social media websites as part of investigations into widespread looting and rioting in London [66, 67], and police in San Francisco disabled access to social networks by cutting off cellphone service as a means to prevent riots due to a police shooting [65]. One U.S. Intelligence strategy in Afghanistan is to focus on answering rudimentary questions about Afghanistan’s social and cultural fabric through tools such as Nexus 7 to tap into the exabytes of information “for leveraging popular support and marginalizing the insurgency” [70]. Yet other’s argue that Nexus 7 lacks models or algorithms.

Models and algorithms have been extensively developed for various engineered networks and multi-agent systems [2]. Consensus is a particular class of network control problem that has been extensively studied where the goal is for the individual nodes to reach an agreement on the states of all agents [71–73]. However, an interesting question that has received little attention is how can such models and methods be applied toward understanding and controlling a social network. How can one produce consensus among a social network (e.g., to manipulate social groups to a desired end)? Motivated towards this

end, the focus of Chapter 6 is to influence the emotions of a socially connected group of individuals to a consensus state.

Various dynamic models have been developed for psychological phenomena, including efforts to model the emotional response of different individuals [74–76]. A dynamic model of love is reported in the work of [74], which describes the time-variation of the emotions displayed by individuals involved in a romantic relationship. In [75], happiness is modeled by a set of differential equations, and the time evolution of one’s happiness in response to external inputs is examined. A mathematical model of fear is also described in the work of [76].

Fractional-order differential equations are a generalization of integer-order differential equations which exhibit a non-local property where the next state of a system not only depends upon its current state but also upon its historical states starting from the initial time [77]. This property has motivated researchers to explore the use of fractional-order systems as a model for various phenomena in natural and engineered systems, and in relation to the current context, have also been explored as a potentially more appropriate model of psychological behavior. For example, the integer-order dynamic models of love and happiness developed in [74] and [75] were revisited in [78] and [79], where the models were generalized to fractional-order dynamics, since a person’s emotional response is influenced by past experiences and memories. However, the results in [74, 75, 78, 79] focus on an individual’s emotion model, without considering the interaction among individuals in the context of a social network where rapid and widespread influences from the social peers can prevail.

Instead of studying an individual model of a person’s emotional response, Chapter 6 develops an approach to influence the interaction of a person’s emotions within a social network. Motivated by the non-local property of fractional-order systems, the emotional response of individuals in the network are modeled by fractional-order dynamics whose states depend on influences from social bonds. Within this formulation, the social group

is modeled as a networked fractional system. The first apparent result that investigated the coordination of networked fractional systems is [80], in which linear time invariant systems are considered and where the interaction between agents is modeled as a link with a constant weight. In this chapter, the social bond between two persons is considered as a weight for the associated edge in the graph measuring the closeness of the relationship between the individuals. In comparison to [80], the main challenge in this work is that social bonds are time varying parameters which depends on the emotional states of individuals. Previous stability analysis tools such as examining the Eigenvalues of linear systems for fractional-order systems (cf. [79–81]) are not applicable to the time-varying system in Chapter 6. To achieve these objectives of maintaining existing social bonds among individuals (i.e., social controls or influences should not be so aggressive that they isolate or break bonds between people in the social group) and emotion synchronization in the social network (i.e., an agreement on the emotion states of all individuals), a decentralized potential function is developed in Chapter 6, and asymptotic convergence of each emotion state to the common equilibrium in the social network is then analyzed via a Metzler Matrix [42] and a Mittag-Leffler stability [82] approach.

#### 1.4 Contributions

The contributions of Chapters 2-6 are discussed as follows:

##### 1. Vision Based Connectivity Maintenance of a Network with Switching

**Topology:** The main contribution in Chapter 2 is the development of a two level control framework for connectivity maintenance and cooperation of multi-agent systems. Each agent is equipped with an omnidirectional camera and wireless communication capabilities, which indicates that each agent is able to see the other agents within its field of view and can communicate with other agents within its communication zone to exchange information. Motivated to reduce the use of interagent radio communication for the maintenance of network connectivity, a two level graph is developed, where all agents are categorized as either clusterheads or

regular nodes. A high level graph is composed of all clusterheads and the motion of the clusterheads is controlled to maintain existing connections among them. A low level graph composed of all regular nodes is controlled to maintain connectivity with respect its specific clusterhead. Image feedback is used as the primary method to maintain connectivity among agents while wireless communication is only used to broadcast information when a specific topology change occurs. One benefit of using image feedback as a primary tool is that radio communication may not be applicable in some dynamic, hostile, or tactical environments, and even when radio communication is possible the network bandwidth may be required for distributing other data. Another contribution of this work is the development of the artificial potential field based controllers to maintain the existing links connected in both low and high level graph all the time, and to ensure that a group of agents switches from one connected configuration to another without disconnecting the network in process.

- 2. Network Connectivity Preserving Formation Stabilization and Obstacle Avoidance via A Decentralized Controller:** decentralized control method is developed in Chapter 3 to enable a group of agents to achieve a desired global configuration while maintaining global network connectivity and avoiding obstacles, using only local feedback and no radio communication between the agents for navigation. Each agent is equipped with a range sensor (e.g., camera) to provide local feedback of the relative trajectory of other agents within a limited sensing region, and a transceiver to broadcast information to immediate neighbors. By modeling the interaction among the agents as a graph, and given a connected initial graph with desired neighborhood between agents, the developed method achieves convergence to a desired configuration and maintenance of network connectivity using a decentralized navigation function approach which uses only local feedback information. By using a local range sensor (and not requiring knowledge of the complete network

structure as in methods that use a graph Laplacian), an advantageous feature of the developed decentralized controller is that no inter-agent communication is required (i.e., communication free global decentralized group behavior). That is, connectivity is maintained so that radio communication is available when required for various task/mission scenarios, but communication is not required to navigate, enabling stealth modes of operation. Collision avoidance and network connectivity are embedded as constraints in the navigation function. By proving that the distributed control scheme is a valid navigation function, the multi-agent system is guaranteed to converge to and stabilize the desired configuration.

- 3. Network Connectivity Preserving Formation Reconfiguration for Identical Agents From An Arbitrary Connected Initial Graph:** Achieving a desired formation for a group of identical agents with limited sensing and communication capabilities from an arbitrarily connected initial graph is considered in Chapter 4. The local interaction among agents is modeled by a dynamic graph and the goal is to achieve a desired formation which is characterized by a given inter-agent distance from an arbitrary connected initial graph while maintaining network connectivity in a decentralized manner. Contrary to the limitation in most existing work in formation control (cf. [2, 26, 27] and their references) where the absolute or relative poses of the agents are prespecified, and the initial topology requires to be a supergraph of the desired topology, a novel formation control technique is developed in Chapter 4, in which the robots are identical and can take any position in the final topology. That is, we do not wish to specify which nodes in the initial topology will take which positions in the final topology; rather, we only care that there is an agent in each position specified in the final topology. Assuming that the final topology is a tree, a prefix labeling and routing algorithm from [52] is modified to specify the neighborhood of each agent according to the desired formation allowing the agents to interchange their roles, and determine the required movement for all nodes to

achieve the desired formation. By modeling the network connectivity as an artificial obstacle, a navigation function based control scheme is developed in this chapter to guarantee the network connectivity by maintaining the neighborhood among agents determined by the prefix labeling algorithm, and ensure the convergence of all agents to the desired configuration with collision avoidance among agents using local information (i.e., local sensing and communication). An information flow is then proposed from the work of [53] and [54] to specify the required movement for extra agents to their destination nodes. The information flow-based approach generally provides a path with more freedom for the motion of extra nodes without partitioning the network connectivity and allows communication links to be formed or broken in a smooth manner without introducing discontinuity. Convergence is proven using Rantzer’s Dual Lyapunov Theorem [55].

4. **Ensuring Network Connectivity for Nonholonomic Robots During Decentralized Rendezvous:** Assuming a range sensor (e.g., camera) provides local feedback of the relative trajectory of other robots within a limited sensing region and a transceiver is used to broadcast information to immediate neighbors on each robot, the objective in Chapter 5 is to reposition and reorient a group of wheeled robots with nonholonomic constraints to a common setpoint with a desired orientation while maintaining network connectivity during the evolution. A distinguishing feature of this work is that it also considers a cooperative objective of maintaining the network connectivity during network regulation for a group of mobile robots. Another feature of the developed decentralized controller is that, using local sensing information, no inter-agent communication is required (i.e., communication-free global decentralized group behavior). That is, network connectivity is maintained so that the radio communication is available when required for various tasks, but communication is not required for regulation. Using a dipolar navigation function framework, the multi-robot system is guaranteed to maintain connectivity and be

stabilized at a common destination with a desired orientation without being trapped by local minima. Moreover, the result can be extended to other applications by replacing the objective function in the navigation function to accommodate different tasks, such as formation control, flocking, and other applications.

5. **Influencing Emotional Behavior in Social Network:** Instead of studying networked control problems in engineering as in Chapter 2-5, Chapter 6 investigates an approach to influence the interaction of a person's emotions within a social network. Using graph theory, a social network is modeled as an undirected graph, where an individual in the social network is represented as a vertex in the graph, and the social relationship between two individuals is represented as an edge connecting two vertices. The social bond between two persons is considered as a weight for the associated edge in the graph measuring the closeness of the relationship between the individuals. Motivated by the non-local property of fractional-order systems, where the next state of a system not only depends upon its current state but also upon its historical states starting from the initial time, the emotional response of individuals in a social network is modeled by fractional-order dynamics whose states depend on influences from social bonds. Within this formulation, the social group is modeled as a networked fractional system. Contrary to the first apparent result that investigated the coordination of networked fractional systems in [80], in which linear time invariant systems are considered and where the interaction between agents is modeled as a link with a constant weight, the main feature in this chapter is that social bonds are time varying parameters which depends on the emotional states of individuals. Previous stability analysis tools such as examining the Eigenvalues of linear systems for fractional-order systems (cf. [79–81]) are no longer applicable to the time-varying system in this chapter. This chapter also considers a social bond threshold on the ability of two people to influence each other's emotions. To ensure interaction among individuals, one objective is to maintain existing social bonds

among individuals above the prespecified threshold all the time (i.e., social controls or influences should not be so aggressive that they isolate or break bonds between people in the social group). Another objective is to design a distributed controller for each individual, using local emotional states from social neighbors, to achieve emotion synchronization in the social network (i.e., an agreement on the emotion states of all individuals). To achieve these objectives, a decentralized potential function is developed to encode the control objective of emotion synchronization, where maintenance of social bonds is modeled as a constraint embedded in the potential function. Asymptotic convergence of each emotion state to the common equilibrium in the social network is then analyzed via a Metzler Matrix [42] and a Mittag-Leffler stability [82] approach.

## 1.5 Dissertation Outline

Chapter 1 serves as an introduction, where the motivation, problem statement, literature review and the contributions of the dissertation are discussed.

Chapter 2 describes a two level control framework for connectivity maintenance and cooperation of multi-agent systems. Artificial potential field based controllers are developed to maintain existing links connected in both low and high level graphs all the time, and also ensure that a group of agents switches from one connected configuration to another without disconnecting the network in process.

Chapter 3 provides a decentralized control method based on the navigation function formalism to enable a group of agents to achieve a desired global configuration from a connected initial graph with desired neighborhood between agents, while maintaining global network connectivity and avoiding obstacles, using only local feedback and no radio communication between the agents for navigation. The performance of the decentralized control method is illustrated through simulations.

Chapter 4 illustrates a novel formation control strategy for a group of identical agents with limited sensing and communication capabilities to achieve a desired formation from

an arbitrarily connected initial condition. A prefix labeling and routing algorithm is modified to specify the neighborhood of each agent according to the desired formation allowing the agents to interchange their roles, and determine the required movement for all nodes to achieve the desired formation. A navigation function based control scheme is developed to guarantee the network connectivity by maintaining the neighborhood among agents determined by the prefix labeling algorithm, and ensure the convergence of all agents to the desired configuration with collision avoidance among agents using local information (i.e., local sensing and communication). Simulation results are provided to illustrate the developed strategy.

Chapter 5 develops a dipolar navigation function and corresponding time-varying continuous controller to reposition and reorient a group of wheeled robots with nonholonomic constraints, while maintaining the network connectivity during the mission, by using only local sensing feedback information from neighbors. Simulation results demonstrate the performance of the developed approach.

Chapter 6 extends the approaches developed in previous chapters to provide a means to influence the human emotion for a group of individual in a social network. The social interactions among individuals in a social network are modeled as an undirected graph with each vertex representing an individual and each edge representing a social bond between individuals. By modeling the emotional response of individuals in the network as fractional-order dynamics whose states depend on influences from social bonds, a decentralized control method is developed to manipulate the social group to a common emotional state while maintaining existing social bonds (i.e., without isolating peers in the group). Asymptotic convergence to a common equilibrium point (i.e., emotional state) of the networked fractional-order system is proved by using Mittag-Leffler stability.

Chapter 7 concludes the dissertation by summarizing the work and discussing some remaining open problems that require further investigation.

CHAPTER 2  
VISION BASED CONNECTIVITY MAINTENANCE OF A NETWORK WITH  
SWITCHING TOPOLOGY

In most applications of a multi-agent system, agents need to coordinate and communicate to take appropriate decisions to fulfill a pre-specified goal. In this chapter, each robot is assumed to be equipped with an omnidirectional camera that can measure the relative position of the other agents in its sensing area, and some form of transceiver that can be used to broadcast information to local nodes. Two moving agents can communicate with each other if they remain within a specific distance. As agents move to perform some mission objective, it is paramount to ensure that the group of agents remain connected (i.e., the group does not partition). Motivated to reduce interagent radio communication, a network connectivity maintenance objective is considered in this chapter that relies primarily on image feedback. A two level control strategy is developed in [83], where all agents in the team are categorized as clusterheads or regular nodes. A high level graph is composed of all clusterheads and the motion of the clusterheads is controlled to maintain existing connections among them. A low level graph composed of all regular nodes is controlled to maintain connectivity with respect its specific clusterhead. Connectivity of the network is maintained using image feedback only unless a clusterhead change is required. If the clusterhead changes and the network needs to reorganize the topology, only then is the wireless communication used to alert the nodes of the topology change. Artificial potential field based controllers are then developed to maintain the existing links connected in both low and high level graphs all the time and to ensure that a group of agents switches from one connected configuration to another without disconnecting the network in process.

### 2.1 Problem Formulation

Consider a network composed of  $N$  agents, where agent  $i$  moves according to the following kinematics:

$$\dot{x}_i(t) = u_i(t), \quad i \in \mathcal{V} = \{1, \dots, N\} \quad (2-1)$$

where  $x_i(t) \in \mathbb{R}^2$  denotes the position of agent  $i$  in a two dimensional (2D) plane at time  $t$ , and  $\mathbf{x}(t) \in \mathbb{R}^{2N}$  denotes the stack position vectors of all agents. In (2-1),  $u_i(t) \in \mathbb{R}^2$  denotes the velocity of agent  $i$  (i.e. the control input). The interaction of the group is modeled as a *dynamic graph*, in the sense that it evolves in time with its connectivity governed by the kinematics of the agents (2-1). This time varying property gives rise to the notion of a dynamic graph,  $\mathcal{G}(t) = (\mathcal{V}, \mathcal{E}(t))$ , in which the set of links  $\mathcal{E}(t)$  is time varying and each component in  $\mathcal{V}$  stands for the index of an agent. Given the assumption that each agent is equipped with an omnidirectional camera and wireless communication capabilities, two different graph models need to be specified: a communication graph and a visibility graph. Each graph is composed of different types of nodes: clusterheads and regular nodes, and the interaction between the nodes in each graph is modeled in a different way.

### 2.1.1 Communication Graph

Inter-agent communication is modeled in terms of a time-varying communication graph  $\mathcal{G}_c = (\mathcal{V}, \mathcal{E}_c(t))$  with the index set of nodes  $\mathcal{V}$  and set of edges

$$\mathcal{E}_c(t) = \{(i, j) \in \mathcal{V} \times \mathcal{V} \mid \|x_{ij}\| \leq R_c\}. \quad (2-2)$$

In (2-2), each node is located at a position  $x_i$ ,  $\|x_{ij}\| \in \mathbb{R}^+$  is defined as

$$\|x_{ij}\| = \|x_i - x_j\|, \quad (2-3)$$

and  $R_c$  denotes the maximum communication radius. The communication graph  $\mathcal{G}_c$  is an undirected graph in the sense that nodes  $i$  can influence node  $j$  and vice versa. An undirected communication link between nodes  $i$  and  $j$  is denoted by  $(i, j)$  when  $\|x_{ij}\| \leq R_c$ . The index set of neighbors of node  $i$  is denoted by

$$\mathcal{N}_i^c = \{j : j \neq i \mid j \in \mathcal{V}, (i, j) \in \mathcal{E}_c\}.$$

### 2.1.2 Visibility Graph

Each agent is capable of sensing a disk area with the maximum radius  $R_v \leq R_c$ , so that any two agents are able to communicate with each other as long as they can see each other. The visibility graph is modeled as a undirected time-varying graph  $\mathcal{G}_v = (\mathcal{V}, \varepsilon_v(t))$  with the index set of nodes  $\mathcal{V}$  and set of edges

$$\varepsilon_v = \{(i, j) \in \mathcal{V} \times \mathcal{V} \mid \|x_{ij}\| \leq R_v\}.$$

For the visibility graph, the edge  $(i, j)$  is undirected indicating that, if node  $i$  can see node  $j$ , node  $j$  can also see node  $i$ . The index set of neighbors of node  $i$  is denoted by  $\mathcal{N}_i^v = \{j : j \neq i \mid j \in \mathcal{V}, (i, j) \in \varepsilon_v(t)\}$ . The subsequent development is based on the assumption that the distance between two nodes can be estimated from the image feedback (e.g., using methods as in [84]).

### 2.1.3 Connectivity Maintenance

Since  $R_v \leq R_c$ , a sufficient goal to ensure  $\mathcal{G}_c$  remains connected is to ensure the visibility graph  $\mathcal{G}_v$  remains connected. For simplicity, the following development is based on the assumption that  $R_v = R_c = R$  without loss of generality. To understand connectivity for each graph, consider Fig 2-1. For the communication graph, if node  $i$  in Fig 2-1 is connected to node  $j$  and node  $j$  is connected to node  $k$ , then node  $i$  is also connected to node  $k$  through edge  $(i, j)$  and  $(j, k)$ . Node  $i$  and node  $k$  may exchange information in  $\mathcal{G}_c$ , to achieve a desired cooperative motion. If Fig 2-1 is considered as a visibility graph, then although node  $j$  can be seen by node  $i$  and node  $k$  can be seen by node  $j$ , node  $i$  is not capable of sharing information with node  $k$ . The communication graph is considered connected if every node in  $\mathcal{G}_c$  is reachable from every other node by a series of edges.

The goal in this chapter is to develop a decentralized image-feedback controller (i.e., velocity input) for each agent so that  $\mathcal{G}_c$  remains connected despite clusterhead shifts (i.e., when a clusterhead role shifts from one node to a regular node). The advantage is that the

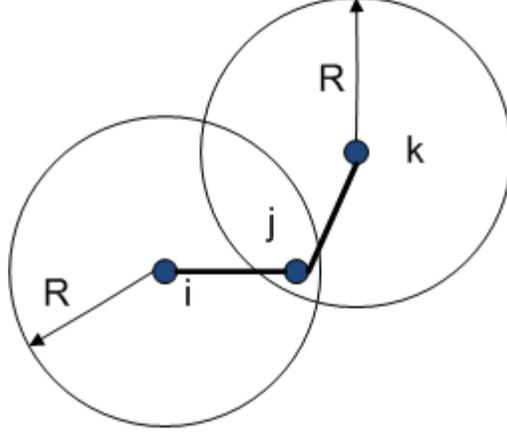


Figure 2-1. Model of visibility graph.

network maintenance is achieved without radio communication, except when a clusterhead shift needs to occur. When the topology changes due to a clusterhead shift, the new role of node is broadcast across the wireless network.

## 2.2 Control Strategy

Motivated by the idea of a communication backbone [85, 86], a two level network structure is proposed. The basic idea is to group all nodes into  $m$  subsets. Each subset contains a one (and only one) special node defined as *clusterhead*, where  $\mathcal{V}_{CH} = \{1, \dots, m\}$  denotes the index set of clusterheads, and the set of clusterheads forms a high level network graph, represented as  $\mathcal{G}^{high}(t)$ . Specifically, the high level network subgraph is composed of clusterheads only, which is a small subset of the group, providing a hierarchical organization of the original network. The high level network subgraph is defined as  $\mathcal{G}^{high}(t) = (\mathcal{V}_{CH}, \mathcal{E}^{high})$ , where  $\mathcal{E}^{high} = \{(i, j) \in \mathcal{V}_{CH} \times \mathcal{V}_{CH} \mid \|x_{ij}\| \leq R\}$ .

All the remaining nodes in each subgraph are defined as a *regular nodes*, where  $\mathcal{V}_{RN} = \{m + 1, \dots, N\}$  denotes the index set of regular nodes. The  $m$  subsets form the low level network, represented as  $\mathcal{G}_i^{low}(t)$ . Specifically, the low level network subgraph is defined as  $\mathcal{G}^{low}(t) = \{\mathcal{G}_1^{low}, \dots, \mathcal{G}_m^{low}\}$ . Each  $\mathcal{G}_i^{low}(t)$  forms a connected subgraph of  $\mathcal{G}_v(t)$  and only one particular node is selected as a clusterhead in each  $\mathcal{G}_i^{low}(t)$ . Note that  $\cap_{i=1}^m \mathcal{G}_i^{low}(t) = \emptyset$ , which means  $\mathcal{G}_i^{low}(t)$  is mutually exclusive to each other, and

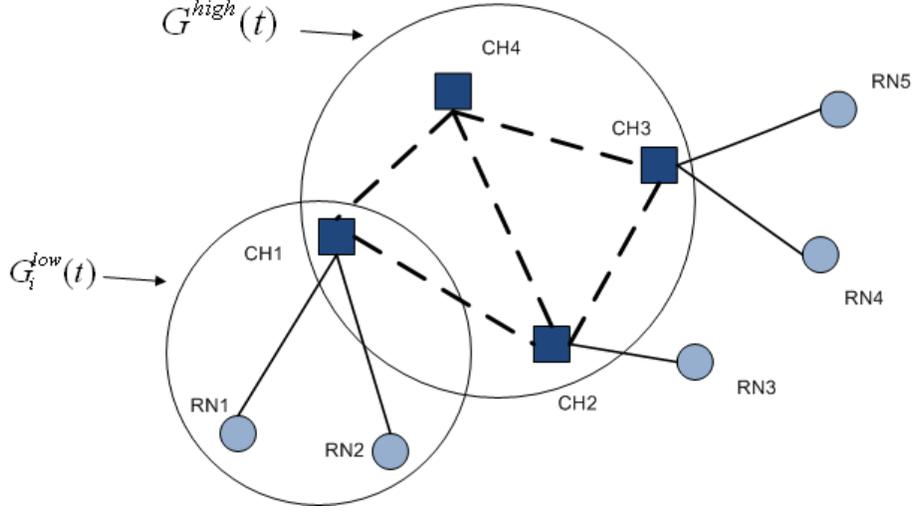


Figure 2-2. Schematic topology of underlying network.

$\cup_{i=1}^m \mathcal{G}_i^{low}(t) = \mathcal{G}_v(t)$ . Since only local information can be obtained by vision sensors, we require that the selected clusterhead can be seen by all regular nodes in each  $\mathcal{G}_i^{low}(t)$ , and each regular node in  $\mathcal{G}_i^{low}(t)$  moves under the constraint that it must stay connected to its clusterhead for all time. Hence, each low level network subgraph  $\mathcal{G}_i^{low}(t)$  has a fixed topology. This two graph structure is depicted in Fig. 2-2, where CH stands for clusterhead and RN stands for regular node. As indicated in Fig. 2-2,  $\{CH1, CH2, CH3, CH4\}$  forms the high level network subgraph  $\mathcal{G}^{high}(t)$ , while  $\{\{CH1, RN1, RN2\}, \{CH2, RN3\}, \{CH3, RN5, RN4\}, \{CH4\}\}$  forms the low level network graph  $\mathcal{G}^{low}(t)$ .

The key to maintain the network connectivity is to maintain connectivity within each subset (i.e., ensure each  $\mathcal{G}_i^{low}(t)$  is individually connected) and maintain connectivity of the  $\mathcal{G}^{high}(t)$  graph. The graphs  $\mathcal{G}_i^{low}(t)$  and  $\mathcal{G}^{high}(t)$  are initially specified, but events can occur that require a clusterhead to change roles with a regular node in  $\mathcal{G}_i^{low}(t)$ . Information-driven methods such as those described in [87] and [88] can be used to dynamically select clusterheads for different tasks. The development in this chapter simply assumes that some process determines the need for a clusterhead and regular node to change roles.

From a systems theory perspective, the underlying network graph dynamics are considered to have a transient and steady-state response. A steady-state topology is when

the roles of the clusterheads and regular nodes remain constant. The control objective during steady-state is to ensure that all regular nodes move to maintain connectivity with the respective clusterhead within  $\mathcal{G}_i^{low}(t)$  and ensure that all clusterheads maintain connectivity within  $\mathcal{G}^{high}(t)$ . In steady-state, no new edges are formed when one node enters other node's sensing radius. In other words, the underlying graph has a fixed topology in the sense that the edges of  $\mathcal{G}_i^{low}(t)$  and  $\mathcal{G}^{high}(t)$  do not change, but the relative position of the nodes within the graph can dynamically change. Connectivity during steady-state is maintained by image feedback alone.

A transient topology is when the overall graph switches from one connected configuration to another without disconnecting. The network can become transient when the role of a node is changed and new edges are created under some rule. To guarantee the connectivity during a transient stage, wireless communication has to be used to broadcast the new role of nodes to the neighbors. Once the new roles of the nodes has been broadcast, then all nodes resume steady-state where the nodes use only image feedback.

The topology will become transient due to changes in mission objectives or topology disturbances. For example, the role of RN1 in Fig. 2-2 may need to change to become a new clusterhead. When the topology undergoes a reconfiguration, a two step strategy is investigated. First, RN1 broadcasts its role-change through immediate neighbors to every node in the group. Radio communication is terminated when all nodes have been updated. Then, under image feedback, the nodes start to form a new connected  $G^{high}$  and  $G_i^{low}$ . Since no radio communication is allowed, each node only has local information within its sensing region. CH3 needs to move toward CH2 first, and, whenever an edge between CH1 and CH3 is created, it moves to CH1 to get close enough to RN1. Likewise, new edges are created for CH4 and CH2 once they can be seen by RN1. Although new edges are created among clusterheads, there is no edge created for regular nodes, even if some other nodes enter its sensing region. In other words, all regular nodes move with its respective clusterhead. As a result, each subgraph  $\mathcal{G}_i^{low}$  can be represented as one single

node, represented as a clusterhead. As long as the clusterheads are connected, the whole graph is connected. One benefit of this structure is that network with large number of nodes can be scaled down.

## 2.3 Control Design

### 2.3.1 Potential Field

The goal in this section is to design distributed control laws  $u_i(t)$  for all nodes to guarantee the connectivity of  $\mathcal{G}_v(t)$ . The set  $\mathcal{N}_i^v(t)$  is time varying and dependent on the relative positions of the nodes. Nodes within distances less than  $R$  are interacting with each other through a potential force and a potential function is used for connectivity maintenance, as well as collision avoidance.

An attractive potential field is defined as  $\varphi_{ij} : \mathbb{R}^2 \rightarrow \mathbb{R}^+$ , which is a nonnegative function of the distance between nodes  $i$  and  $j$ , i.e.  $\varphi_{ij} = \varphi_{ij}(\|x_{ij}\|)$ . The purpose of the attractive force is to guarantee that node  $j$  will never leave the sensing zone of node  $i$ , if node  $j$  is initially located at a distance less than  $R$  from node  $i$ . The attractive potential field is to regulate distances between agents within the range  $(0, R)$ . Some properties are required to make  $\varphi_{ij}$  a qualified potential function:

- 1)  $\varphi_{ij}(\|x_{ij}\|) \rightarrow \infty$  as  $\|x_{ij}\| \rightarrow R$ .
- 2)  $\varphi_{ij}(\|x_{ij}\|)$  is  $C^1$  for  $\|x_{ij}\| \in (0, R)$  and  $\frac{\partial \varphi_{ij}}{\partial \|x_{ij}\|} > 0$ , if  $\|x_{ij}\| \in (0, R)$ .
- 3)  $\varphi_{ij}(\|x_{ij}\|) = 0$  when  $\|x_{ij}\| > R$ .

A repulsive potential field is defined as  $\psi_{ij} : \mathbb{R}^2 \rightarrow \mathbb{R}^+$ , which is a differentiable (except at point  $\|x_{ij}\| = 0$ ), nonnegative function of the distance between nodes  $i$  and  $j$ , i.e.  $\psi_{ij} = \psi_{ij}(\|x_{ij}\|)$ . The purpose of the repulsive force is to guarantee collisions avoidance between node  $i$  and node  $j$  as they get close to each other. Some properties are required to make  $\psi_{ij}$  a qualified potential function:

- 1)  $\psi_{ij}(\|x_{ij}\|) \rightarrow \infty$  as  $\|x_{ij}\| \rightarrow 0$ .
- 2)  $\psi_{ij}(\|x_{ij}\|) = 0$ , and  $\frac{\partial \psi_{ij}}{\partial x_i} = 0$ , if  $\|x_{ij}\| \geq R$ .
- 3)  $\frac{\partial \psi_{ij}}{\partial \|x_{ij}\|} < 0$ , if  $\|x_{ij}\| \in (0, R)$ , and  $\frac{\partial \psi_{ij}}{\partial \|x_{ij}\|} = 0$ , if  $\|x_{ij}\| \geq R$ .

Property 2) guarantees that

$$\sum_{j \in \mathcal{N}_i^v(t)} \frac{\partial \psi_{ij}}{\partial x_i} = \sum_{j \neq i} \frac{\partial \psi_{ij}}{\partial x_i}.$$

The importance of this property is that, unlike an attractive force, the time varying set  $\mathcal{N}_i^v(t)$  does not introduce any discontinuity to the system when one node enters the sensing zone of another node. Inspired by [40], [89], [90], a function  $\varphi_{ij}^*(\|x_{ij}\|)$  is introduced to smooth the discontinuity when a new edge is formed. To capture the newly formed edge, a set  $\mathcal{N}_i^*(t)$  is defined as  $\mathcal{N}_i^*(t) = \{j \in \mathcal{V}, j \neq i \mid \|x_{ij}\| \leq R - \epsilon\}$ , where  $0 < \epsilon \ll R$ . The set of edges is updated as:  $\mathcal{E}_v(t) = \mathcal{E}_v(t^-) \cup \mathcal{E}_v^*(t)$ , where  $\mathcal{E}_v^*(t) = \{(i, j) \mid ((i, j) \notin \mathcal{E}_v(t^-)) \wedge (j \in \mathcal{N}_i^*(t))\}$ . The function  $\varphi_{ij}^*$  is defined with following properties:

- 1)  $\varphi_{ij}^* = \varphi_{ij}$  if  $\|x_{ij}\| \leq R - \epsilon$ .
- 2)  $\varphi_{ij}^* = \text{const}$  and  $\frac{\partial \varphi_{ij}^*}{\partial x_i} = 0$  if  $\|x_{ij}\| \geq R$ .
- 3)  $\varphi_{ij}^*$  is  $C^1$  everywhere and the partial derivative  $\frac{\partial \varphi_{ij}^*}{\partial \|x_{ij}\|} > 0$  for  $R - \epsilon < \|x_{ij}\| < R$ .
- 4)  $\varphi_{ij}^*(R - \epsilon) = \varphi_{ij}(R - \epsilon)$  and  $\frac{\partial \varphi_{ij}^*(R - \epsilon)}{\partial \|x_{ij}\|} = \frac{\partial \varphi_{ij}(R - \epsilon)}{\partial \|x_{ij}\|}$ .

The function switches from  $\varphi_{ij}^*$  to  $\varphi_{ij}$  during a switching state, and a new edge is created whenever a node  $j$  is a distance less than  $R - \epsilon$  with respect to node  $i$ . It seems that  $\varphi_{ij}^*$  is used to capture the potential among node  $i$  and nodes outside of its sensing zone, which is a violation of a decentralized approach. Actually, according to Property 2),  $\varphi_{ij}^*$  is carefully designed so that its partial derivative with respect to  $x_i$  is 0 when  $\|x_{ij}\| \geq R$ . The only element that contributes to the controller is  $\frac{\partial \varphi_{ij}^*}{\partial \|x_{ij}\|}$ ,  $\|x_{ij}\| \in (R - \epsilon, R)$ . Although node  $j$  is in the sensing region of node  $i$ , no new edge is created. In addition,  $\varphi_{ij}^*$  is  $C^1$  everywhere. Hence, the switch to  $\varphi_{ij}$  is sufficiently smooth when a node  $j$  enters the sensing zone of node  $i$ .

### 2.3.2 Controller for Steady State

In each subgraph  $\mathcal{G}_i^{low}$ , a regular node is attracted by its clusterhead only and repelled by all the adjacent nodes. The total potential of regular node  $i, i \in V_{RN}$ , is:

$$U_i^r = \varphi_{ik} + \sum_{j \in \mathcal{N}_i^v(t)} \psi_{ij}, \quad (2-4)$$

where  $k, k \in V_{CH}$ , denotes the index of the corresponding clusterhead in  $\mathcal{G}_i^{low}$ . The control law for a regular node is designed as

$$u_i^r(t) = -\frac{\partial U_i^r}{\partial x_i}. \quad (2-5)$$

The motion of a clusterhead is not affected by regular nodes, and a clusterhead only moves with the constraint to ensure connectivity and collision avoidance in  $\mathcal{G}^{high}$ . The composite potential of clusterhead  $i, i \in V_{CH}$ , is given by:

$$U_i^c = \sum_{(i,j) \in \mathcal{E}^{high}} \varphi_{ij} + \sum_{(i,j) \in \mathcal{E}^{high}} \psi_{ij} + U_i^T, \quad (2-6)$$

where  $U_i^T$  denotes a task potential to model a required performance, which imposes an attractive potential on node  $i$ . The control law for the clusterheads is designed as

$$u_i^c(t) = -\frac{\partial U_i^c}{\partial x_i}. \quad (2-7)$$

### 2.3.3 Controller for Switching State

Collision avoidance and network connectivity must be maintained even when the topology undergoes a transition. As described in Section 2.2, the motion of regular nodes is dictated by the motion of the parent clusterhead. The total potential and control law for regular node  $i$  is the same as (2-4) and (2-5) in steady state conditions. However, the potential for the clusterhead nodes change. Specifically, the composite potential of

clusterhead  $i \in V_{CH}$  is given by

$$U_i^c = \sum_{(i,j) \in E(t)} \varphi_{ij} + \sum_{(i,j) \notin E(t)} \varphi_{ij}^* + \sum_{j \neq i} \psi_{ij}, \quad (2-8)$$

where the set  $E(t) \subset \varepsilon^{high}(t)$  denotes a time varying set of edges developed based on the switching strategy in Section 2.2. The goal of new set  $E(t)$  is to guide clusterheads to form a new steady state. Note that there are two main differences between (2-6) and (2-8). First, there is no  $U_i^T$  in (2-8). The term  $U_i^T$  is designed to perform tasks in steady state. The goal of the switching state is to reshape the topology to a new steady topology. There is no need to keep  $U_i^T$  during the switching process. Secondly, the function  $\varphi_{ij}^*$  is used to take care of the discontinuity that is caused by new edge formation. Based on the developed composite potential, the control law for clusterheads is designed as

$$u_i^c(t) = -\frac{\partial U_i^c}{\partial x_i}. \quad (2-9)$$

An initial connected underlying graph is required to guarantee the connectivity for all the future time.

## 2.4 Connectivity Analysis

**Proposition 2.1.** *For steady state, if the network graph  $\mathcal{G}_v(t)$  is connected at  $t = t_0$ , then connectivity and collision avoidance is guaranteed with the controller proposed in (2-5) and (2-7) for  $t > t_0$ .*

*Proof.* The topology of  $\mathcal{G}_v(t)$  is static in steady state in the sense that new edges are not formed. In each subgraph  $\mathcal{G}_i^{low}$ , regular nodes move with respect to its clusterhead, and in subgraph  $\mathcal{G}^{high}$ , clusterheads move with the constraint that the connectivity is ensured. A Lyapunov candidate functional is designed as

$$V = \sum_{i \in \mathcal{V}_{RN}} U_i^r + \sum_{i \in \mathcal{V}_{CH}} U_i^c. \quad (2-10)$$

Based on (2-4) and (2-6), as an agent gets close to a collision or as the graph gets closer to partitioning, then  $V(\mathbf{x}(t))$  approaches infinity. Taking time derivative of (2-10) and

substituting for (2-5) and (2-7), yields

$$\begin{aligned}
\dot{V} &= \sum_{i \in \mathcal{V}_{RN}} \frac{\partial U_i^r}{\partial x_i} \dot{x}_i + \sum_{i \in \mathcal{V}_{CH}} \frac{\partial U_i^c}{\partial x_i} \dot{x}_i \\
&= - \sum_{i \in \mathcal{V}_{RN}} \left\| \frac{\partial U_i^r}{\partial x_i} \right\|^2 - \sum_{i \in \mathcal{V}_{CH}} \left\| \frac{\partial U_i^c}{\partial x_i} \right\|^2 \\
&\leq 0.
\end{aligned} \tag{2-11}$$

The expressions in (2-10) and (2-11) imply that  $V(\mathbf{x}(t)) \leq V(\mathbf{x}(t_0))$ . Since the system is initially collision free and connected at  $t_0$ , then  $V(\mathbf{x}(t_0)) < \infty$ , and the graph is ensured to remain collision free and connected for all  $t \geq t_0$  provided the graph topology remains in a steady state condition.  $\square$

**Proposition 2.2.** *During the switching process, connectivity and collision avoidance of the network graph  $\mathcal{G}(t)$  is guaranteed by the controller proposed in (2-5) and (2-9).*

*Proof.* Proposition 2.1 indicates that connectivity is guaranteed in each  $\mathcal{G}_i^{low}$ . To show the graph  $\mathcal{G}_v(t)$  is connected during a clusterhead switch, we only need to show that once any two clusterheads come into a distance less than or equal to  $R - \epsilon$  for the first time, they will remain connected to each other, i.e. the distance between them is strictly less than  $R$  for all future time. To examine this scenario, a Lyapunov candidate functional is designed as:

$$V = \sum_{i \in \mathcal{V}_{CH}} \left( \sum_{(i,j) \in E(t)} \varphi_{ij} + \sum_{(i,j) \notin E(t)} \varphi_{ij}^* + \sum_{i \neq j} \psi_{ij} \right). \tag{2-12}$$

An attractive potential function  $\varphi_{ij}$  is a discontinuous function at the point  $\|x_{ij}\| = R$  while the repulsive function  $\psi_{ij}$  is a differentiable function. Whenever a node  $j$  forms a new edge with node  $i$ , the function  $\varphi_{ij}^*$  is switched to  $\varphi_{ij}$  in a sufficiently smooth manner, so that  $V$  is continuously differentiable. Taking the time derivative of  $V$  and substituting (2-5) and (2-9) yields  $\dot{V} \leq 0$ , and hence,  $V(\mathbf{x}(t)) \leq V(\mathbf{x}(t_0)) < \infty$ . It is known that  $V \rightarrow \infty$  when  $\|x_{ij}\| \rightarrow R$  for at least one pair of nodes. Hence, all pairs of nodes that did

not initially form an edge move so that new edges are formed so that the communication graph remains connected. □

## 2.5 Simulation

Preliminary simulation results illustrate the performance of the proposed control strategy. A group of 7 nodes with kinematics given in (2-1) are distributed in the plane with an initially connected underlying graph. Assume that each node has a sensing zone of  $R = 1$  m. When two agents are adjacent, a line is drawn between them to show the connectivity.

A group of 7 nodes evolved under the control law proposed in Section 2.3. In Fig. 2-3 and Fig. 2-4, the rectangular nodes represent clusterheads and circles represent regular nodes. The dashed lines identify the link among clusterheads, while solid lines identify the link between a regular node and a clusterhead. At  $t = 0$ , an initial connected graph is generated. During time interval  $t \in (0, 120)$ , the group of nodes moves in steady state. The topology is maintained during node motion, as shown in Fig. 2-3. One clusterhead is simulated with a task function to move along a designed trajectory,  $P_y = 2 \sin(0.2P_x)$ , where  $P_y$  and  $P_x$  denotes the stack  $x$  and  $y$  coordinate vector respectively. In Fig. 2-3, all nodes move in a desired manner.

To simulate the performance of a switching state, the topology changes at  $t = 121$  in the sense that one regular node switches its role to a new clusterhead, while one clusterhead changes its role to a regular node. The new clusterhead is tasked with the objective to move along the desired trajectory,  $P_y = -2 \sin(0.2P_x)$ , from its current position. Fig. 2-4 illustrates how these nodes move to reshape the topology to form a new steady state topology without disconnecting the group.

## 2.6 Summary

A two stage control framework is proposed for connectivity maintenance and cooperation of a multi-agent system using image feedback. The idea is to group all nodes into two subgraphs, a high level network subgraph and several low level network subgraphs. The

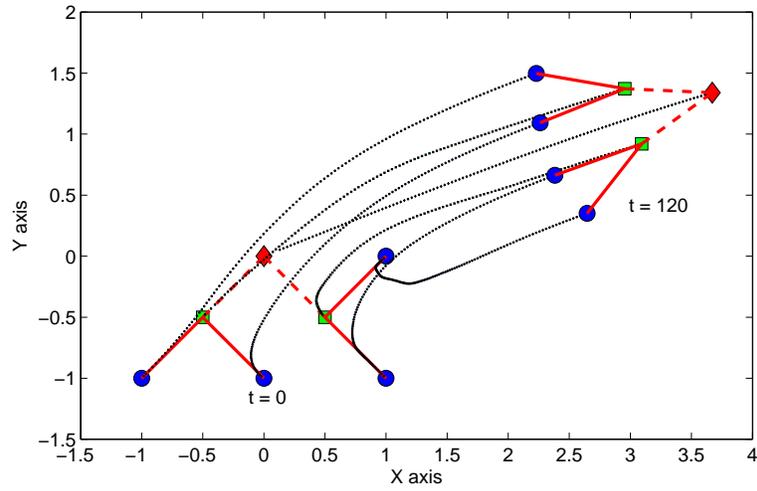


Figure 2-3. Evolution of nodes during time interval of  $t \in (0, 120)$ .

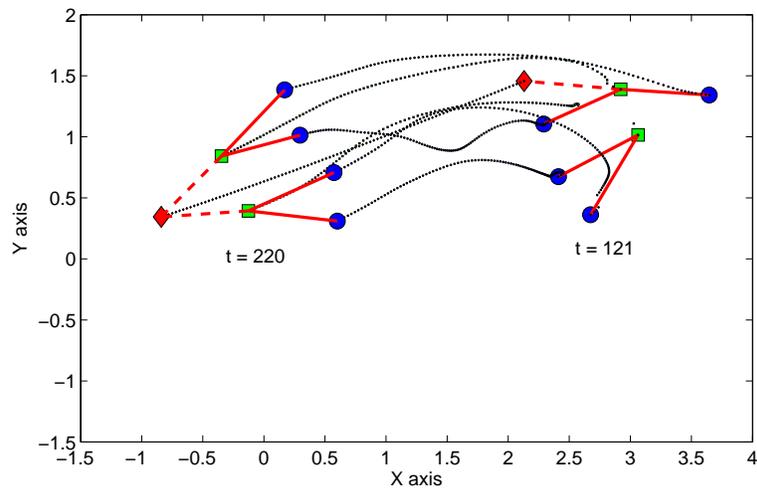


Figure 2-4. Evolution of nodes during time interval of  $t \in (121, 220)$ .

key to maintain the network connectivity is to ensure the connectivity of high level subgraph and the connectivity of each low level subgraph. A potential-field-based controller is used to guarantee the connectivity, as well as collision avoidance. Future efforts will focus on more simulations with more nodes and more switching to examine the interplay of the nodes, including cases where multiple nodes shift from clusterheads at the same time.

## CHAPTER 3

### NETWORK CONNECTIVITY PRESERVING FORMATION STABILIZATION AND OBSTACLE AVOIDANCE VIA A DECENTRALIZED CONTROLLER

In this chapter, a navigation function framework is used to develop a decentralized controller (see also [91]) that guarantees a multi-agent system to achieve a desired configuration while preserving the network connectivity during the motion. By using a local range sensor (and not requiring knowledge of the complete network structure as in methods that use a graph Laplacian), an advantageous feature of the developed decentralized controller is that no inter-agent communication is required (i.e., communication free global decentralized group behavior). The goal is to maintain connectivity so that radio communication is available when required for various task/mission scenarios, but communication is not required to navigate, enabling stealth modes of operation. Collision avoidance and network connectivity are embedded as constraints in the navigation function. By proving that the distributed control scheme is a valid navigation function, the multi-agent system is guaranteed to converge to and stabilize at the desired configuration.

#### 3.1 Problem Formulation

Consider a network composed of  $N$  agents in the workspace  $\mathcal{F}$ , where agent  $i$  moves according to the following kinematics:

$$\dot{q}_i = u_i, \quad i = 1, \dots, N \tag{3-1}$$

where  $q_i \in \mathbb{R}^2$  denotes the position of agent  $i$  in a two dimensional (2D) plane, and  $u_i \in \mathbb{R}^2$  denotes the velocity of agent  $i$  (i.e., the control input). The workspace  $\mathcal{F}$  is assumed to be circular and bounded with radius  $R$ , and  $\partial\mathcal{F}$  denotes the boundary of  $\mathcal{F}$ . Each agent in  $\mathcal{F}$  is represented by a point-mass with a limited communication and sensing capability encoded by a disk area. It is assumed that each agent is equipped with a range sensor and wireless communication capabilities. Two moving agents can communicate with each other if they are within a distance  $R_c$ , while the agent can sense stationary obstacles or other agents within a distance  $R_s$ . For simplicity and without loss of generality, the

following development is based on the assumption that the sensing area coincides with the communication area, i.e.,  $R_c = R_s$ . Further, it is assumed that all the agents have equal actuation capabilities. A set of fixed points,  $p_1, \dots, p_M$ , are defined to represent  $M$  stationary obstacles in the workspace  $\mathcal{F}$ , and the index set of obstacles is denoted as  $\mathcal{M} = \{1, \dots, M\}$ . The assumption of point-obstacles is not restrictive, since a large class of shapes can be mapped to single points through a series of transformations [92], and this “point-world” topology is a degenerate case of the “sphere-world” topology [29].

The interaction of the system is modeled as a *dynamic graph*, in the sense that the system evolves in time governed by the agent kinematics in (3–1). The dynamic graph is denoted as  $\mathcal{G}(t) = (\mathcal{V}, \mathcal{E}(t))$ , where  $\mathcal{V} = \{1, \dots, N\}$  denotes the set of nodes, and  $\mathcal{E}(t) = \{(i, j) \in \mathcal{V} \times \mathcal{V} \mid d_{ij} \leq R_c\}$  denotes the set of time varying edges, where node  $i$  and node  $j$  are located at a position  $q_i$  and  $q_j$ , and  $d_{ij} \in \mathbb{R}^+$  is the relative distance defined as  $d_{ij} = \|q_i - q_j\|$ . In graph  $\mathcal{G}(t)$ , each node  $i$  represents an agent, and the edge  $(i, j)$  denotes a link between agent  $i$  and  $j$  when they stay within a distance  $R_c$ . Nodes  $i$  and  $j$  are also called *one-hop neighbors* of each other. The set of one-hop neighbors of node  $i$  (i.e., all the agents within the sensing zone of agent  $i$ ) is given by  $\mathcal{N}_i = \{j, j \neq i \mid j \in \mathcal{V}, (i, j) \in \mathcal{E}\}$ . One objective in this work is to have the multi-agent system converge to a desired configuration, determined by a formation matrix  $c_{ij} \in \mathbb{R}^2$  representing the desired relative position of node  $i$  with an adjacent node  $j \in \mathcal{N}_i^f$ , where  $\mathcal{N}_i^f \subset \mathcal{N}_i$  denotes the set of nodes required to form a prespecified relative position with node  $i$  in the desired configuration. The neighborhood  $\mathcal{N}_i$  is a time varying set since nodes may enter or leave the communication region of node  $i$  at any time instant, while  $\mathcal{N}_i^f$  is a static set which is specified by the desired configuration. The desired position of node  $i$ , denoted by  $q_{di}$ , is defined as

$$q_{di} = \left\{ q_i \mid \|q_i - q_j - c_{ij}\|^2 = 0, j \in \mathcal{N}_i^f \right\}.$$

An edge  $(i, j)$  is only established between nodes  $i$  and  $j$  if  $j \in \mathcal{N}_i^f$ .

A *collision region*<sup>1</sup> is defined for each agent  $i$  as a small disk with radius  $\delta_1 < R_c$  around the agent  $i$ , such that any other agent  $j \in \mathcal{N}_i$ , or obstacle  $p_k, k \in \mathcal{M}$ , inside this region is considered as a potential collision with agent  $i$ . To ensure connectivity, an *escape region* for each agent  $i$  is defined as the outer ring of the communication area with radius  $r, R_c - \delta_2 < r < R_c$ , where  $\delta_2 \in \mathbb{R}$  is a predetermined buffer distance. Edges formed with any node  $j \in \mathcal{N}_i^f$  in the escape region are in danger of breaking.

The objective is to develop a decentralized controller  $u_i$  that uses relative position information from the range sensor to regulate a connected initial graph to a desired configuration while maintaining network connectivity and avoiding collisions with other agents and obstacles in radio silence. To achieve this goal, the subsequent development is based on the following assumptions.

**Assumption 3.1.** *The initial graph  $\mathcal{G}$  is connected within a desired neighborhood, (i.e., the desired neighbors of an agent are initially within the agent's sensing zone), and those initial positions do not coincide with some unstable equilibria (i.e., saddle points).*

**Assumption 3.2.** *The desired formation matrix  $c_{ij}$  is specified initially and is achievable, which implies that the desired configuration will not lead to a collision and the desired configuration will not lead to a partitioned graph, (i.e.,  $\delta_1 < \|c_{ij}\| < R_c - \delta_2$ ).*

### 3.2 Control Design

The goal in this section is to develop a decentralized controller using only local sensing to navigate the agents to a desired formation while maintaining network connectivity. Consider a decentralized navigation function candidate  $\varphi_i : \mathcal{F}_i \rightarrow [0, 1]$  for each node  $i$  as

$$\varphi_i = \frac{\gamma_i}{(\gamma_i^\alpha + \beta_i)^{1/\alpha}}, \quad (3-2)$$

---

<sup>1</sup> The potential collision for node  $i$  in this work not only refers to the fixed obstacles, but also other moving nodes or the workspace boundary, which are currently located in its collision region.

where  $\alpha \in \mathbb{R}^+$  is a tuning parameter,  $\gamma_i : \mathbb{R}^2 \rightarrow \mathbb{R}^+$  is the goal function, and  $\beta_i : \mathbb{R}^2 \rightarrow [0, 1]$  is a constraint function for node  $i$ . The goal function  $\gamma_i$  in (3-2) encodes the control objective of node  $i$ , specified in terms of the desired relative position with respect to the adjacent nodes  $\{j \in \mathcal{N}_i^f\}$ , and drives the system to a desired configuration<sup>2</sup>. The goal function is designed as

$$\gamma_i(q_i, q_j) = \sum_{j \in \mathcal{N}_i^f} \|q_i - q_j - c_{ij}\|^2. \quad (3-3)$$

The constraint function  $\beta_i$  in (3-2) is designed as

$$\beta_i = B_{i0} \prod_{j \in \mathcal{N}_i^f} b_{ij} \prod_{k \in \mathcal{N}_i \cup \mathcal{M}_i} B_{ik}, \quad (3-4)$$

to ensure collision avoidance and network connectivity by only accounting for nodes and obstacles located within its sensing area during each time instant. Specifically, the constraint function in (3-4) is designed to vanish whenever node  $i$  intersects with one of the constraints in the environment, (i.e., if node  $i$  touches a fixed obstacle, the workspace boundary, other nodes, or departs away from its adjacent nodes  $\{j \in \mathcal{N}_i^f\}$  to a distance of  $R_c$ ). In (3-4),  $b_{ij} \triangleq b(q_i, q_j) : \mathbb{R}^2 \rightarrow [0, 1]$  ensures connectivity of the network graph (i.e., guarantees that nodes  $\{j \in \mathcal{N}_i^f\}$  will never leave the communication zone of node  $i$  if node  $j$  is initially connected to node  $i$ ) and is designed as

$$b_{ij} = \begin{cases} 1 & d_{ij} \leq R_c - \delta_2 \\ -\frac{1}{\delta_2^2}(d_{ij} + 2\delta_2 - R_c)^2 + \frac{2}{\delta_2}(d_{ij} + 2\delta_2 - R_c) & R_c - \delta_2 < d_{ij} < R_c \\ 0 & d_{ij} \geq R_c. \end{cases} \quad (3-5)$$

---

<sup>2</sup> The formation objective  $\gamma_i$  is developed based on the desire to control the distance and relative bearings between nodes. For some applications, only the relative distance between nodes is important, and the objective could be rewritten as  $\gamma_i = \sum_{j \in \mathcal{N}_i^f} (\|q_i - q_j\| - \|c_{ij}\|)^2$ ; however, this objective can introduce redundant desired configurations. Future efforts could consider this alternative objective, where an approach such as [7] may be explored to address the multiple desired minima.

Also in (3-4),  $B_{ik} \triangleq B(q_i, q_k) : \mathbb{R}^2 \rightarrow [0, 1]$ , for point  $k \in \mathcal{N}_i \cup \mathcal{M}_i$ , where  $\mathcal{M}_i$  indicates the set of obstacles within the sensing area of node  $i$  at each time instant, ensures that node  $i$  is repulsed from other nodes or obstacles to prevent a collision, and is designed as

$$B_{ik} = \begin{cases} -\frac{1}{\delta_1^2}d_{ik}^2 + \frac{2}{\delta_1}d_{ik} & d_{ik} < \delta_1 \\ 1 & d_{ik} \geq \delta_1. \end{cases} \quad (3-6)$$

Similarly, the function  $B_{i0}$  in (3-4) is used to model the potential collision of node  $i$  with the workspace boundary, where the positive scalar  $B_{i0} \in \mathbb{R}$  is designed similar to  $B_{ik}$  by replacing  $d_{ik}$  with  $d_{i0}$ , where  $d_{i0} \in \mathbb{R}^+$  is the relative distance of the node  $i$  to the workspace boundary defined as  $d_{i0} = R - \|q_i\|$ .

Assumption 3.2 guarantees that  $\gamma_i$  and  $\beta_i$  will not be zero simultaneously. The navigation function candidate achieves its minimum of 0 when  $\gamma_i = 0$  and achieves its maximum of 1 when  $\beta_i = 0$ . For  $\varphi_i$  to be a navigation function, it has to satisfy the following conditions [29]:

- 1) smooth on  $\mathcal{F}$  (at least a  $\mathcal{C}^1$  function [38]);
- 2) admissible on  $\mathcal{F}$ , (uniformly maximal on  $\partial\mathcal{F}$  and constraint boundary);
- 3) polar on  $\mathcal{F}$ , ( $q_{di}$  is a unique minimum);
- 4) a Morse function, (critical points<sup>3</sup> of the navigation function are non-degenerate).

If  $\varphi_i$  is a Morse function and  $q_{di}$  is a unique minimum of  $\varphi_i$  (i.e.,  $q_{di}$  is polar on  $\mathcal{F}$ ), then almost all initial positions (except for a set of points of measure zero) asymptotically approach the desired position  $q_{di}$  [29]. In addition, the negative gradient of the navigation function is bounded if it is an admissible Morse function with a single minimum at the desired destination [29]. An example of the generated artificial potential field is shown in

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<sup>3</sup> A point  $p$  in the workspace  $\mathcal{F}$  is a critical point if  $\nabla_{q_i}\varphi_i|_p = 0$ .

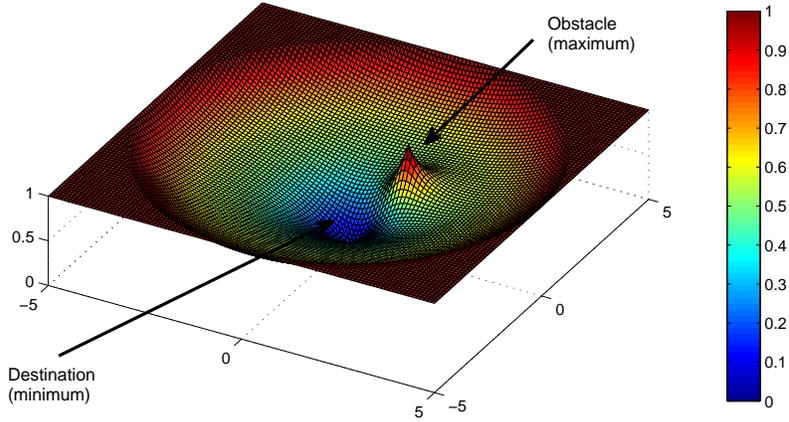


Figure 3-1. An example of the artificial potential field generated for a disk-shaped workspace with destination at the origin and an obstacle located at  $[1, 1]^T$ .

Fig. 3-1, in which the destination is assigned a minimum potential value and the obstacle is assigned a maximum potential value.

Based on the definition of the navigation function candidate, the decentralized controller for each node is designed as

$$u_i = -K \nabla_{q_i} \varphi_i, \quad (3-7)$$

where  $K$  is a positive gain, and  $\nabla_{q_i} \varphi_i$  is the gradient of  $\varphi_i$  with respect to  $q_i$ . Hence, the controller in (3-7) is bounded and yields the desired performance by steering node  $i$  along the direction of the negative gradient of  $\varphi_i$  if (3-2) is a navigation function.

### 3.3 Connectivity and Convergence Analysis

The free configuration workspace  $\mathcal{F}_i \subset \mathcal{F}$  is a compact connected analytic manifold for node  $i$ ,  $\mathcal{F}_i \triangleq \{\mathbf{q} \mid \beta_i(\mathbf{q}) > 0\}$ , and  $\mathbf{q}$  denotes the stacked position vector of node  $i$ . The boundary of  $\mathcal{F}_i$  is defined as  $\partial \mathcal{F}_i \triangleq \beta_i^{-1}(0)$ . The narrow set around a potential collision for node  $i$  is defined as

$$\mathcal{B}_{i,k}^B(\varepsilon) \triangleq \{\mathbf{q} \mid 0 < B_{ik} < \varepsilon, \varepsilon > 0, k \in \mathcal{N}_i \cup \mathcal{M}_i\},$$

and a narrow set around a potential connectivity constraint is defined as

$$\mathcal{B}_{i,j}^b(\varepsilon) \triangleq \{\mathbf{q} \mid 0 < b_{ij} < \varepsilon, \varepsilon > 0, j \in \mathcal{N}_i^f\}.$$

The set  $\mathcal{B}_0(\varepsilon) = \{\mathbf{q} \mid 0 < B_{i0} < \varepsilon, \varepsilon > 0\}$  is used to denote a narrow set around a potential collision of node  $i$  with workspace boundary. Inspired by the seminal work in [29],  $\mathcal{F}_i$  is partitioned into five subsets  $\mathcal{F}_0(\varepsilon)$ ,  $\mathcal{F}_1(\varepsilon)$ ,  $\mathcal{F}_2(\varepsilon)$ ,  $\mathcal{F}_3(\varepsilon)$ , and  $\mathcal{F}_{di}(\varepsilon)$  as

$$\mathcal{F}_i = \mathcal{F}_{di} \cup \mathcal{F}_0(\varepsilon) \cup \mathcal{F}_1(\varepsilon) \cup \mathcal{F}_2(\varepsilon) \cup \mathcal{F}_3(\varepsilon),$$

where the set of desired configurations for node  $i$  is defined as  $\mathcal{F}_{di} \triangleq \{\mathbf{q} \mid \gamma_i(\mathbf{q}) = 0\}$ . The sets  $\mathcal{F}_0(\varepsilon)$ ,  $\mathcal{F}_1(\varepsilon)$ ,  $\mathcal{F}_2(\varepsilon)$  and  $\mathcal{F}_3(\varepsilon)$  describe the regions near the workspace boundary, near the potential collision constraint, near the connectivity constraint and away from all constraints for node  $i$ , respectively, and are defined as

$$\mathcal{F}_0(\varepsilon) \triangleq \mathcal{B}_0(\varepsilon) - \mathcal{F}_{di},$$

$$\mathcal{F}_1(\varepsilon) \triangleq \bigcup_{k=1}^{\xi_i + \vartheta_i} \mathcal{B}_{i,k}^B(\varepsilon) - \mathcal{F}_{di},$$

$$\mathcal{F}_2(\varepsilon) \triangleq \bigcup_{j=1}^{\zeta_i} \mathcal{B}_{i,j}^b(\varepsilon) - \mathcal{F}_{di},$$

and

$$\mathcal{F}_3(\varepsilon) \triangleq \mathcal{F}_i - \{\mathcal{F}_{di} \cup \mathcal{F}_0(\varepsilon) \cup \mathcal{F}_1(\varepsilon) \cup \mathcal{F}_2(\varepsilon)\},$$

where  $\xi_i$ ,  $\vartheta_i$ ,  $\zeta_i \in \mathbb{R}^+$  denote the number of nodes in the set  $\mathcal{N}_i$ ,  $\mathcal{M}_i$  and  $\mathcal{N}_i^f$ , respectively.

Based on the partition of  $\mathcal{F}_i$ , Proposition 3.1 to 3.8 are subsequently introduced to ensure that the designed function in (3-2) is a navigation function. Proposition 3.1 shows that network connectivity is ensured if the initial graph is connected. To establish the convergence properties of the potential field, Proposition 3.2 shows the system converges to the set of critical points under the controller in (3-7), and Proposition 3.3 to 3.8

together ensure that  $q_{di}$  is the unique minimum, and the other critical points are saddle points, by proving that (3–2) has the properties of a navigation function. Proposition 3.3 shows  $q_{di}$  is a minimum in  $\varphi_i$ . Proposition 3.4 shows there is no minima on the workspace boundary. Proposition 3.5 ensures all the critical points can be pushed away from  $\mathcal{F}_3(\varepsilon)$  by choosing  $\alpha$  big enough. Proposition 3.6 shows that  $\varphi_i$  is a Morse function, while Proposition 3.7 and 3.8 indicate that the critical points in  $\mathcal{F}_0(\varepsilon)$ ,  $\mathcal{F}_1(\varepsilon)$  and  $\mathcal{F}_2(\varepsilon)$  are not minima. Proposition 3.5 to 3.8 together guarantee that  $q_{di}$  is the unique minimum in the workspace. The following assumptions are used to prove Proposition 3.6 to 3.8.

**Assumption 3.3.** *No obstacles or other agents are assumed to stay within the collision region of node  $i$ , when node  $i$  is very close to breaking the communication link with a node  $j \in \mathcal{N}_i^f$  (i.e., node  $i$  and node  $j$  belong to the region  $\mathcal{B}_{i,j}^b(\varepsilon)$ ).*

**Assumption 3.4.** *The region  $\mathcal{B}_{i,k}^B(\varepsilon)$  for  $k \in \mathcal{N}_i \cup \mathcal{M}_i$  is disjoint. This assumption implies a negligible probability of more than one simultaneous collision with node  $i$ .*

### 3.3.1 Connectivity Analysis

**Proposition 3.1.** *If the graph  $\mathcal{G}$  is connected initially and  $j \in \mathcal{N}_i^f$ , then (3–7) ensures nodes  $i$  and  $j$  will remain connected for all time.*

*Proof. Proof:* Consider node  $i$  located at a point  $q_0 \in \mathcal{F}$  that causes  $\prod_{j \in \mathcal{N}_i^f} b_{ij} = 0$ , which will be true when either only one node  $j$  is about to disconnect from node  $i$  or when more than one node is about to disconnect with node  $i$  simultaneously. These two possibilities are considered in the following two cases.

Case 1: There is only one node  $j \in \mathcal{N}_i^f$  for which  $b_{ij}(q_0, q_j) = 0$  and  $b_{il}(q_0, q_l) \neq 0 \forall l \in \mathcal{N}_i^f, l \neq j$ . The gradient of  $\varphi_i$  with respect to  $q_i$  is

$$\nabla_{q_i} \varphi_i = \frac{\alpha \beta_i \nabla_{q_i} \gamma_i - \gamma_i \nabla_{q_i} \beta_i}{\alpha (\gamma_i^\alpha + \beta_i)^{\frac{1}{\alpha} + 1}}. \quad (3-8)$$

Since  $b_{ij} = 0$ , the constraint function  $\beta_i = 0$  from (3–4). Thus, the gradient  $\nabla_{q_i} \varphi_i$  evaluated at  $q_0$  can be expressed as  $\nabla_{q_i} \varphi_i|_{q_0} = -\frac{\gamma_i \nabla_{q_i} \beta_i}{\alpha \gamma_i^{\alpha+1}} \Big|_{q_0}$ . Based on the fact that  $\beta_i$  can

be expressed as the product  $\beta_i = b_{ij}\bar{b}_{ij}$ , where

$$\bar{b}_{ij}(q_0, q_j) = B_{i0} \prod_{l \in \mathcal{N}_i^f, l \neq j} b_{il} \prod_{k \in \mathcal{N}_i \cup \mathcal{M}_i} B_{ik}, \quad (3-9)$$

and  $\nabla_{q_i} b_{ij}$  is computed as

$$\nabla_{q_i} b_{ij} = \begin{cases} 0 & d_{ij} < R_c - \delta_2 \text{ or } d_{ij} > R_c \\ -\frac{2(d_{ij} + \delta_2 - R_c)(q_i - q_j)}{\delta_2^2 d_{ij}} & R_c - \delta_2 \leq d_{ij} \leq R_c, \end{cases} \quad (3-10)$$

the gradient of  $\beta_i$  evaluated at  $q_0$  can be obtained as  $\nabla_{q_i} \beta_i|_{q_0} = -\frac{2\bar{b}_{ij}}{\delta R_c}(q_i - q_j)$ . Since  $K_i$ ,  $\gamma_i$ ,  $\alpha$ ,  $\bar{b}_{ij}$  and  $\delta$  are all positive terms, (3-7), and  $\nabla_{q_i} \beta_i|_{q_0}$  can be used to determine that the controller (i.e., the negative gradient of  $\nabla_{q_i} \varphi_i$ ) is along the direction of  $q_j - q_i$ , which implies node  $i$  is forced to move toward node  $j$  to ensure connectivity. That is, based on the design of  $b_{ij}$  in (3-5) and its gradient in (3-10), whenever a node enters the escape region of node  $i$ , an attractive force is imposed on node  $i$  to ensure connectivity.

Case 2<sup>4</sup>: Consider two nodes  $j, l \in \mathcal{N}_i^f$ , where  $b_{ij} = 0$  and  $b_{il} = 0$  (i.e.,  $\|q_i - q_j\| = R_c$  and  $\|q_i - q_l\| = R_c$ ) simultaneously. In this case,  $\beta_i = 0$  and  $\nabla_{q_i} \beta_i$  is a zero vector, (3-8) can be used to determine that  $q_0$  is a critical point (i.e.,  $\nabla_{q_i} \varphi_i|_{q_0} = 0$ ), and the navigation function achieves its maximum value at the critical point (i.e.,  $\varphi_i|_{q_0} = 1$ ). Since  $\varphi_i$  is maximized at  $q_0$ , no open set of initial conditions can be attracted to  $q_0$  under the control law designed in (3-7).

From the development in Case 1 and Case 2, the control law in (3-7) ensures that all nodes  $j \in \mathcal{N}_i^f$  remain connected with node  $i$  for all time.  $\square$

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<sup>4</sup> Case 2 can be extended to more than two nodes without loss of generality.

### 3.3.2 Convergence Analysis

**Proposition 3.2.** *The system in (3-1) converges to the largest invariant set (i.e., the set of critical points  $S = \{q \mid \nabla_{q_i} \varphi_i|_q = 0\}$ ) under the controller in (3-7), provided that the tuning parameter in (3-2) satisfies  $\alpha > \Theta$ , where  $\Theta = \max \left\{ \sqrt{\frac{|c_1|}{c_3}}, \frac{|c_2|}{c_3} \right\}$ .*

*Proof.* Consider a Lyapunov candidate  $V(\mathbf{q}) = \sum_{i=1}^N \varphi_i$ , where  $\mathbf{q}$  is the stacked states of all nodes, i.e.,  $\mathbf{q} = [q_1, \dots, q_N]^T$ . The time derivative of  $V$  is computed as

$$\dot{V} = (\nabla V)^T \dot{\mathbf{q}} = -K \sum_{i=1}^N \sum_{j=1}^N (\nabla_{q_i} \varphi_i)^T (\nabla_{q_i} \varphi_j),$$

which can be further separated as

$$\begin{aligned} \dot{V} = & -K \sum_{i: \nabla_{q_i} \varphi_i = 0} \left( \|\nabla_{q_i} \varphi_i\|^2 + \sum_{j \neq i} (\nabla_{q_i} \varphi_i)^T (\nabla_{q_i} \varphi_j) \right) \\ & -K \sum_{i: \nabla_{q_i} \varphi_i \neq 0} \left( \|\nabla_{q_i} \varphi_i\|^2 + \sum_{j \neq i} (\nabla_{q_i} \varphi_i)^T (\nabla_{q_i} \varphi_j) \right). \end{aligned} \quad (3-11)$$

When all nodes are located at the critical points in (3-11),  $\dot{V} = 0$ . To show that the set of critical points are the largest invariant set, it requires that  $\dot{V}$  is strictly negative, whenever there exists at least one node  $i$  such that  $\nabla_{q_i} \varphi_i \neq 0$ . Since  $\nabla_{q_i} \varphi_i \neq 0$  for at least one node, (3-11) can be rewritten as

$$\dot{V} = -K \sum_{i: \nabla_{q_i} \varphi_i \neq 0} \left( \|\nabla_{q_i} \varphi_i\|^2 + \sum_{j \neq i} (\nabla_{q_i} \varphi_i)^T (\nabla_{q_i} \varphi_j) \right). \quad (3-12)$$

To ensure that  $\dot{V} < 0$  in (3-12), it is sufficient to require that  $\sum_{j \neq i} (\nabla_{q_i} \varphi_i)^T (\nabla_{q_i} \varphi_j) > 0$ , which can be expanded by using (3-8) as

$$\frac{(\beta_i \nabla_{q_i} \gamma_i - \frac{\gamma_i}{\alpha} \nabla_{q_i} \beta_i)^T}{(\gamma_i^\alpha + \beta_i)^{\frac{1}{\alpha} + 1}} \left( \sum_{j \neq i} \frac{(\beta_j \nabla_{q_i} \gamma_j - \frac{\gamma_j}{\alpha} \nabla_{q_i} \beta_j)}{(\gamma_j^\alpha + \beta_j)^{\frac{1}{\alpha} + 1}} \right) > 0. \quad (3-13)$$

Since  $\gamma_i, \beta_i$  are all positive from (3-3) and (3-4), and  $\gamma_i, \beta_i$  can not be zero simultaneously from Assumption 3.2, the inequality in (3-13) is valid provided

$$\left( \beta_i \nabla_{q_i} \gamma_i - \frac{\gamma_i}{\alpha} \nabla_{q_i} \beta_i \right)^T \left( \sum_{j \neq i} \left( \beta_j \nabla_{q_i} \gamma_j - \frac{\gamma_j}{\alpha} \nabla_{q_i} \beta_j \right) \right) > 0,$$

which can be simplified as

$$\frac{1}{\alpha^2}c_1 + \frac{1}{\alpha}c_2 + c_3 > 0, \quad (3-14)$$

where

$$\begin{aligned} c_1 &= \gamma_i (\nabla_{q_i} \beta_i)^T \sum_{j \neq i} \gamma_j \nabla_{q_i} \beta_j, \\ c_2 &= -\beta_i (\nabla_{q_i} \gamma_i)^T \sum_{j \neq i} \gamma_j \nabla_{q_i} \beta_j - \gamma_i (\nabla_{q_i} \beta_i)^T \sum_{j \neq i} \beta_j \nabla_{q_i} \gamma_j, \end{aligned}$$

and

$$c_3 = \beta_i (\nabla_{q_i} \gamma_i)^T \sum_{j \neq i} \beta_j \nabla_{q_i} \gamma_j.$$

In (3-14), since  $\beta_i$  and  $\beta_j$  are positive, and node  $i$  satisfies  $\nabla_{q_i} \varphi_i \neq 0$ ,  $c_3$  is positive from (3-3). Using the fact that  $c_1 \geq -|c_1|$ ,  $c_2 \geq -|c_2|$ , (3-14) can be written as

$$-\frac{1}{\alpha^2} |c_1| - \frac{1}{\alpha} |c_2| > -c_3,$$

which suffices to show that  $\alpha > \max \left\{ \sqrt{\frac{|c_1|}{c_3}} \right\}$  and  $\alpha > \max \left\{ \frac{|c_2|}{c_3} \right\}$ . Therefore, if  $\alpha$  is chosen such that  $\alpha > \Theta$ , where  $\Theta = \max \left\{ \sqrt{\frac{|c_1|}{c_3}}, \frac{|c_2|}{c_3} \right\}$ , the system converges to the set of critical points.  $\square$

**Proposition 3.3.** *The navigation function is minimized at the desired point  $q_{di}$ .*

*Proof.* The navigation function  $\varphi_i$  is minimized at a critical point if the Hessian of  $\varphi_i$  evaluated at that point is positive definite. The gradient expression in (3-8) is used to determine if  $q_{di}$  is a critical point. From the definition of  $q_{di}$  and (3-3), the goal function evaluated at the desired point is  $\gamma_i|_{q_{di}} = 0$ . Also, the gradient of the goal function evaluated at the desired point  $q_{di}$  is

$$\nabla_{q_i} \gamma_i|_{q_{di}} = \sum_{j \in \mathcal{N}_i^f} 2(q_{di} - q_j - c_{ij}) = 0.$$

Since  $\gamma_i|_{q_{di}} = 0$  and  $\nabla_{q_i}\gamma_i|_{q_{di}} = 0$ , (3–8) can be used to conclude that  $\nabla_{q_i}\varphi_i|_{q_{di}} = 0$ . Thus, the desired point  $q_{di}$  in the workspace  $\mathcal{F}$  is a critical point of  $\varphi_i$ . The Hessian of  $\varphi_i$  is

$$\begin{aligned} \nabla_{q_i}^2\varphi_i &= \frac{1}{\alpha(\gamma_i^\alpha + \beta_i)^{\frac{1}{\alpha}+2}} \left\{ (\gamma_i^\alpha + \beta_i) \left[ \alpha \nabla_{q_i}\beta_i (\nabla_{q_i}\gamma_i)^T - \nabla_{q_i}\gamma_i (\nabla_{q_i}\beta_i)^T + \alpha\beta_i \nabla_{q_i}^2\gamma_i \right. \right. \\ &\quad \left. \left. - \gamma_i \nabla_{q_i}^2\beta_i \right] - \frac{\alpha+1}{\alpha} [\alpha\beta_i \nabla_{q_i}\gamma_i - \gamma_i \nabla_{q_i}\beta_i] \cdot [\alpha\gamma_i^{\alpha-1} \nabla_{q_i}\gamma_i + \nabla_{q_i}\beta_i]^T \right\}. \end{aligned} \quad (3-15)$$

Using the facts that  $\gamma_i|_{q_{di}} = 0$  and  $\nabla_{q_i}\gamma_i|_{q_{di}} = 0$  and the Hessian of  $\gamma_i$  is

$$\nabla_{q_i}^2\gamma_i = 2\zeta_i I_2, \quad (3-16)$$

where  $I_2$  is the identity matrix in  $\mathbb{R}^{2 \times 2}$ , the Hessian of  $\varphi_i$  evaluated at  $q_{di}$  is given by

$$\nabla_{q_i}^2\varphi_i|_{q_{di}} = 2\beta_i^{-\frac{1}{\alpha}} I_2 \zeta_i.$$

The constraint function  $\beta_i > 0$  at the desired configuration by Assumption 3.2, and  $\zeta_i$  is a positive number. Hence, the Hessian of  $\varphi_i$  evaluated at that point is positive definite.  $\square$

**Proposition 3.4.** *No minima of  $\varphi_i$  are on the boundary of the free workspace  $\mathcal{F}_i$ .*

*Proof.* Consider a point  $q_0 \in \partial\mathcal{F}_i$ . From the definition of  $\partial\mathcal{F}_i$  the constraint function  $\beta_i(q_0) = 0$ . The goal function  $\gamma_i$  is zero only at the desired configuration point, and from Assumption 3.2, the desired configuration cannot be on the boundary of  $\mathcal{F}_i$ . Thus, the goal function  $\gamma_i$  evaluated at  $q_0$  is not zero. Using (3–2) and the facts that  $\beta_i|_{q_0} = 0$  and  $\gamma_i|_{q_0} \neq 0$ ,  $\varphi_i|_{q_0}$  is maximized at any arbitrarily chosen point  $q_0$  on the boundary of  $\mathcal{F}_i$ .  $\square$

**Proposition 3.5.** *For every  $\varepsilon > 0$ , there exists a number  $\Gamma(\varepsilon)$  such that if  $\alpha > \Gamma(\varepsilon)$  no critical points of  $\varphi_i$  are in  $\mathcal{F}_3(\varepsilon)$ .*

*Proof.* From (3–8), any critical point must satisfy  $\alpha\beta_i \nabla_{q_i}\gamma_i = \gamma_i \nabla_{q_i}\beta_i$ . If  $\alpha$  is chosen as

$$\alpha > \sup \frac{\gamma_i \|\nabla_{q_i}\beta_i\|}{\beta_i \|\nabla_{q_i}\gamma_i\|},$$

where sup is taken over  $\mathcal{F}_3(\varepsilon)$ , then from (3–8),  $\varphi_i$  will have no critical points in  $\mathcal{F}_3(\varepsilon)$ .

Since  $\varepsilon = \inf b_{ij} = \inf B_{ik}$  in  $\mathcal{F}_3(\varepsilon)$ , an upper bound  $\sup \frac{\gamma_i \|\nabla_{q_i} \beta_i\|}{\beta_i \|\nabla_{q_i} \gamma_i\|}$  is given as

$$\sup \frac{\gamma_i}{\|\nabla_{q_i} \gamma_i\|} \frac{\|\nabla_{q_i} \beta_i\|}{\beta_i} \leq \Gamma(\varepsilon)$$

where

$$\Gamma(\varepsilon) \triangleq \sup \frac{\gamma_i}{\|\nabla_{q_i} \gamma_i\|} \left( \sum_{j=1, j \neq i}^{\zeta_i} \frac{\sup \|\nabla_{q_i} b_{ij}\|}{\varepsilon} + \sum_{k=0, k \neq i}^{\xi_i + \vartheta_i} \frac{\sup \|\nabla_{q_i} B_{ik}\|}{\varepsilon} \right). \quad (3-17)$$

In (3–17),  $\|\nabla_{q_i} b_{ij}\|$ ,  $\|\nabla_{q_i} B_{ik}\|$  and  $\frac{\gamma_i}{\|\nabla_{q_i} \gamma_i\|}$  are bounded terms in  $\mathcal{F}_3(\varepsilon)$  from (3–3), (3–10)

and the fact that

$$\nabla_{q_i} B_{ik} = \begin{cases} \left(-\frac{2}{\delta_1^2} d_{ik} + \frac{2}{\delta_1}\right) \frac{q_i - q_k}{d_{ik}} & d_{ik} < \delta_1 \\ 0 & d_{ik} \geq \delta_1. \end{cases} \quad (3-18)$$

□

**Proposition 3.6.** *There exists  $\varepsilon_0 > 0$  such that if  $\varepsilon < \varepsilon_0$ , then  $\varphi_i$  is a Morse function.*

*Proof.* The development in [30] and [39] proves that for  $\varphi_i$  to be a Morse function, it is sufficient to show that  $\hat{u}^T (\nabla_{q_i}^2 \varphi_i|_{q_{ci}}) \hat{u}$  is positive for some particular vector  $\hat{u}$  by choosing a small  $\varepsilon$ , where  $q_{ci}$  is a critical point. To show that  $\hat{u}^T (\nabla_{q_i}^2 \varphi_i|_{q_{ci}}) \hat{u}$  is positive for the unit vector

$$\hat{u} \triangleq \frac{q_i - q_j}{\|q_i - q_j\|},$$

(3–15) is used and the Hessian  $\nabla_{q_i}^2 \varphi_i$  evaluated at  $q_{ci}$  is

$$\frac{\alpha \hat{u}^T \left( \nabla_{q_i}^2 \varphi_i|_{q_{ci}} \right) \hat{u}}{(\gamma_i^\alpha + \beta_i)^{-\frac{1}{\alpha} - 1}} = \hat{u}^T \left( \alpha \beta_i \nabla_{q_i}^2 \gamma_i + \frac{(1 - \frac{1}{\alpha}) \gamma_i}{\beta_i} \nabla_{q_i} \beta_i (\nabla_{q_i} \beta_i)^T - \gamma_i \nabla_{q_i}^2 \beta_i \right) \hat{u} \quad (3-19)$$

To facilitate the subsequent analysis, the set of critical points in  $\mathcal{F}_i$  is divided into sets of critical points in regions  $\mathcal{F}_0(\varepsilon)$ ,  $\mathcal{F}_1(\varepsilon)$ , and  $\mathcal{F}_2(\varepsilon)$ . For a case where a critical point

$q_{ci} \in \mathcal{F}_2(\varepsilon)$ , using the fact that  $\nabla_{q_i}\beta_i$  and  $\nabla_{q_i}^2\beta_i$  can be expressed as

$$\nabla_{q_i}\beta_i = \bar{b}_{ij}\nabla_{q_i}b_{ij} + b_{ij}\nabla_{q_i}\bar{b}_{ij}, \quad (3-20)$$

$$\nabla_{q_i}^2\beta_i = \bar{b}_{ij}\nabla_{q_i}^2b_{ij} + (\nabla_{q_i}\bar{b}_{ij}\nabla_{q_i}^Tb_{ij} + \nabla_{q_i}b_{ij}\nabla_{q_i}^T\bar{b}_{ij}) + b_{ij}\nabla_{q_i}^2\bar{b}_{ij}, \quad (3-21)$$

where  $\bar{b}_{ij}$  is defined in (3-9), and the fact that the first term on the right hand side of (3-19) is always positive from (3-16), the subsequent expression can be obtained as

$$\alpha(\gamma_i^\alpha + \beta_i)^{\frac{1}{\alpha}+1}\hat{u}^T \left( \nabla_{q_i}^2\varphi_i|_{q_{ci}} \right) \hat{u} > \gamma_i\Omega, \quad (3-22)$$

where

$$\Omega = \frac{1}{b_{ij}} (a_1b_{ij}^2 + a_2b_{ij} + a_3),$$

with

$$a_1 = \frac{(\alpha - 1) \|\nabla_{q_i}\bar{b}_{ij}\|^2}{\alpha\bar{b}_{ij}} - \hat{u}^T(\nabla_{q_i}^2\bar{b}_{ij})\hat{u},$$

$$a_2 = \frac{2(\alpha - 1)(\nabla_{q_i}\bar{b}_{ij})^T(\nabla_{q_i}b_{ij})}{\alpha} - \bar{b}_{ij}\hat{u}^T(\nabla_{q_i}^2b_{ij})\hat{u} - \hat{u}^T(\nabla_{q_i}\bar{b}_{ij}\nabla_{q_i}^Tb_{ij} + \nabla_{q_i}b_{ij}\nabla_{q_i}^T\bar{b}_{ij})\hat{u},$$

and

$$a_3 = \frac{(\alpha - 1)\bar{b}_{ij}}{\alpha} \|\nabla_{q_i}b_{ij}\|^2.$$

Since  $b_{ij} > 0$ , a necessary condition to show that  $\Omega > 0$  is to prove that

$$a_1b_{ij}^2 + a_2b_{ij} + a_3 > 0, \quad (3-23)$$

where  $a_3 > 0$  if  $\alpha > 1$ . To prove the inequality in (3-23), the following two cases are analyzed.

Case 1: For  $a_1 < 0$ , the inequality in (3-23) is valid if

$$b_{ij} < \frac{-a_2 - \sqrt{a_2^2 - 4a_1a_3}}{2a_1}.$$

Case 2: For  $a_1 \geq 0$ ,  $\Omega$  can be rewritten as  $\Omega \geq a_2 + \frac{a_3}{b_{ij}}$ , which is positive if

$$b_{ij} < \frac{a_3}{|a_2|}.$$

Therefore,  $\Omega > 0$ , and from (3-22),  $\hat{u}^T(\nabla_{q_i}^2 \varphi_i|_{q_{ci}})\hat{u} > 0$  for all cases if  $b_{ij}$  is chosen as

$$b_{ij} < \varepsilon'_0 \triangleq \min \left\{ \frac{-a_2 - \sqrt{a_2^2 - 4a_1a_3}}{2a_1}, \frac{a_3}{|a_2|} \right\}.$$

By using the same process of evaluating the Hessian  $\nabla_{q_i}^2 \varphi_i$  at critical points belonging to  $\mathcal{F}_0(\varepsilon)$  and  $\mathcal{F}_1(\varepsilon)$ , upper bounds  $\varepsilon''_0$  and  $\varepsilon'''_0$  for  $\varepsilon$  can be obtained for  $q_{ci} \in \mathcal{F}_1(\varepsilon)$  and  $q_{ci} \in \mathcal{F}_0(\varepsilon)$  respectively. By choosing  $\varepsilon < \varepsilon_0 = \min \{\varepsilon'_0, \varepsilon''_0, \varepsilon'''_0\}$ , the function  $\Omega$  is guaranteed to be positive which implies all the critical points are non-degenerate critical points of  $\varphi_i$ . □

**Proposition 3.7.** *There exists  $\varepsilon_1 > 0$ , such that  $\varphi_i$  has no local minimum in  $\mathcal{F}_2(\varepsilon)$ , as long as  $\varepsilon < \varepsilon_1$ .*

*Proof.* Consider a critical point  $q_{ci} \in \mathcal{F}_2(\varepsilon)$ . Since  $\varphi_i$  is a Morse function, then if  $\nabla_{q_i}^2 \varphi_i|_{q_{ci}}$  has at least one negative eigenvalue,  $\varphi_i$  will have no minimum in  $\mathcal{F}_2(\varepsilon)$ . To show  $\nabla_{q_i}^2 \varphi_i|_{q_{ci}}$  has at least one negative eigenvalue, a unit vector

$$\hat{v} \triangleq \left( \frac{\nabla_{q_i} \beta_i}{\|\nabla_{q_i} \beta_i\|} \right)^\perp$$

is defined as a test direction to demonstrate that

$$\hat{v}^T \left( \nabla_{q_i}^2 \varphi_i|_{q_{ci}} \right) \hat{v} < 0,$$

where  $(\chi)^\perp$  denotes a vector that is perpendicular to some vector  $\chi$ . Using (3-20) and (3-21),

$$\alpha(\gamma_i^\alpha + \beta_i)^{\frac{1}{\alpha}+1} \Big|_{q_{ci}} \hat{v}^T \left( \nabla_{q_i}^2 \varphi_i|_{q_{ci}} \right) \hat{v} = -\gamma_i \Phi + b_{ij} \Psi,$$

where

$$\Phi = \hat{v}^T \left( \nabla_{q_i} \bar{b}_{ij} \nabla_{q_i}^T b_{ij} + \nabla_{q_i} b_{ij} \nabla_{q_i}^T \bar{b}_{ij} - \bar{b}_{ij} \nabla_{q_i}^2 b_{ij} \right) \hat{v},$$

$$\Psi = \hat{v}^T (\alpha \bar{b}_{ij} \nabla_{q_i}^2 \gamma_i - \gamma_i \nabla_{q_i}^2 \bar{b}_{ij}) \hat{v},$$

and

$$\nabla_{q_i}^2 b_{ij} = \begin{cases} 0 & d_{ij} \leq R_c - \delta_2 \text{ or } d_{ij} \geq R_c \\ \frac{2(\delta_2 - R_c)(q_i - q_j)(q_i - q_j)^T}{\delta_2^2 d_{ij}^3} - \frac{2(d_{ij} + \delta_2 - R_c)}{d_{ij} \delta_2^2} I_2 & R_c - \delta_2 < d_{ij} < R_c. \end{cases} \quad (3-24)$$

Based on Assumption 3.3 and (3-5), (3-6), (3-10), (3-24),  $\nabla_{q_i} \bar{b}_{ij} = 0$  and  $\nabla_{q_i}^2 b_{ij} < 0$ . Since the goal function  $\gamma_i$  and  $\bar{b}_{ij}$  are positive,  $\Phi > 0$ . To ensure  $\hat{v}^T (\nabla_{q_i}^2 \varphi_i|_{q_{ci}}) \hat{v} < 0$ ,  $\varepsilon$  must be selected as  $\varepsilon < \varepsilon_1$  where  $\varepsilon_1 = \inf_{\mathcal{F}_2(\varepsilon)} \frac{|\gamma_i \Phi|}{|\Psi|}$ .  $\square$

**Proposition 3.8.** *There exists  $\varepsilon_2 > 0$ , such that  $\varphi_i$  has no local minimum in  $\mathcal{F}_1(\varepsilon)$  and  $\mathcal{F}_0(\varepsilon)$ , as long as  $\varepsilon < \varepsilon_2$ .*

*Proof.* Consider a critical point  $q_{ci} \in \mathcal{F}_1(\varepsilon)$ . Similar to the proof for Proposition 3.7, the current proof is based on the fact that if  $\hat{w}^T (\nabla_{q_i}^2 \varphi_i|_{q_{ci}}) \hat{w} < 0$  for some particular vector  $\hat{w} \triangleq \left( \frac{q_i - q_k}{\|q_i - q_k\|} \right)^\perp$ , then  $\varphi_i$  will have no minimum in  $\mathcal{F}_1(\varepsilon)$ . To facilitate the subsequent analysis, similar to the definition of  $\bar{b}_{ij}$  in (3-9),  $\beta_i$  can be expressed as the product  $\beta_i = B_{ik} \bar{B}_{ik}$  and  $\bar{B}_{ik}$  is defined as

$$\bar{B}_{ik}(q_i, q_k) = B_{i0} \prod_{j \in \mathcal{N}_i^f} b_{ij} \prod_{l \in \mathcal{N}_i \cup \mathcal{M}_i, l \neq k} B_{il}. \quad (3-25)$$

Using (3-16), (3-18) and (3-25),

$$\alpha(\gamma_i^\alpha + \beta_i)^{\frac{1}{\alpha} + 1} \Big|_{q_{ci}} \hat{w}^T (\nabla_{q_i}^2 \varphi_i|_{q_{ci}}) \hat{w} = \gamma_i \bar{B}_{ik} \Lambda + \gamma_i B_{ik} \Xi,$$

where

$$\Lambda = \nabla_{q_i}^T B_{ik} \frac{\nabla_{q_i} \gamma_i}{\|\nabla_{q_i} \gamma_i\|} 2\zeta_i - \frac{2(\delta_1 - d_{ik})}{d_{ik} \delta_1^2},$$

$$\Xi = \hat{w}^T \left( \frac{\nabla_{q_i}^T \bar{B}_{ik} \nabla_{q_i} \gamma_i}{\|\nabla_{q_i} \gamma_i\|} \nabla_{q_i}^2 \gamma_i + \frac{(1 - \frac{1}{\alpha})}{\beta_{ij}} \nabla_{q_i} \bar{B}_{ik} \nabla_{q_i}^T \bar{B}_{ik} - \nabla_{q_i}^2 \bar{B}_{ik} \right) \hat{w},$$

and

$$\nabla_{q_i}^2 B_{ik} = \begin{cases} \left( -\frac{2}{\delta_1^2} + \frac{2}{d_{ik} \delta_1} \right) I_2 - \frac{2(q_i - q_k)(q_i - q_k)^T}{\delta_1 d_{ik}^3} & d_{ik} < \delta_1 \\ 0 & d_{ik} \geq \delta_1. \end{cases}$$

Since  $d_{ik} < \delta_1$ , and  $\nabla_{q_i}^T B_{ik} \frac{\nabla_{q_i} \gamma_i}{\|\nabla_{q_i} \gamma_i\|}$  can be upper bounded by a positive constant in  $\mathcal{F}_1(\varepsilon)$ , then if  $d_{ik}$  is small enough,  $\Lambda$  is guaranteed to be negative. Hence, there exist a positive scalar  $\varepsilon_{21} = B_{ik}(d_{ik})$ , which is small enough to ensure  $\Lambda < 0$ . To ensure

$$\hat{w}^T \left( \nabla_{q_i}^2 \varphi_i \Big|_{q_{ci}} \right) \hat{w} < 0,$$

$\varepsilon$  must be selected as

$$\varepsilon < \min\{\varepsilon_{21}, \inf_{\mathcal{F}_1(\varepsilon)} \frac{|\Lambda \bar{B}_{ik}|}{|\Xi|}\}.$$

Let  $\hat{x}$  be an unit vector defined as

$$\hat{x} \triangleq \left( \frac{q_i - q_0}{\|q_i - q_0\|} \right)^\perp.$$

The same procedure that was used to show

$$\hat{w}^T \left( \nabla_{q_i}^2 \varphi_i \Big|_{q_{ci}} \right) \hat{w} < 0$$

in  $\mathcal{F}_1(\varepsilon)$  can be followed to obtain another upper bound for  $\varepsilon$ , which ensures

$$\hat{x}^T \left( \nabla_{q_i}^2 \varphi_i \Big|_{q_{ci}} \right) \hat{x} < 0$$

in  $\mathcal{F}_0(\varepsilon)$ . By choosing  $\varepsilon_2$  as the minimum of the upper bound for  $\varepsilon$  developed for  $\mathcal{F}_1(\varepsilon)$  and  $\mathcal{F}_0(\varepsilon)$ ,  $\varphi_i$  is ensured to have no minimum in  $\mathcal{F}_1(\varepsilon)$  and  $\mathcal{F}_0(\varepsilon)$  as long as  $\varepsilon < \varepsilon_2$ .  $\square$

Based on Propositions 3.2 to 3.8, if  $\varepsilon$  is chosen such that  $\varepsilon \leq \min\{\varepsilon_0, \varepsilon_1, \varepsilon_2\}$  then the minima (a critical point) is not in  $\mathcal{F}_0(\varepsilon)$ ,  $\mathcal{F}_1(\varepsilon)$ ,  $\mathcal{F}_2(\varepsilon)$ ,  $\mathcal{F}_3(\varepsilon)$  or the boundary of  $\mathcal{F}_i$ . Thus, the minima has to be in  $\mathcal{F}_{di}(\varepsilon)$  if  $\alpha > \max\{1, \Gamma(\varepsilon), \Theta\}$ . Hence, nodes starting from any initial positions (except for the unstable equilibria) will converge to the desired formation specified by the formation matrix  $c_{ij}$ .

### 3.4 Simulation

Simulation results illustrate the performance of the proposed control strategy. As shown in the Fig. 3-2, a connected initial graph of 40 nodes with kinematics in (3-1) are deployed with desired neighborhood in a workspace of  $R = 30$  m with static obstacles.

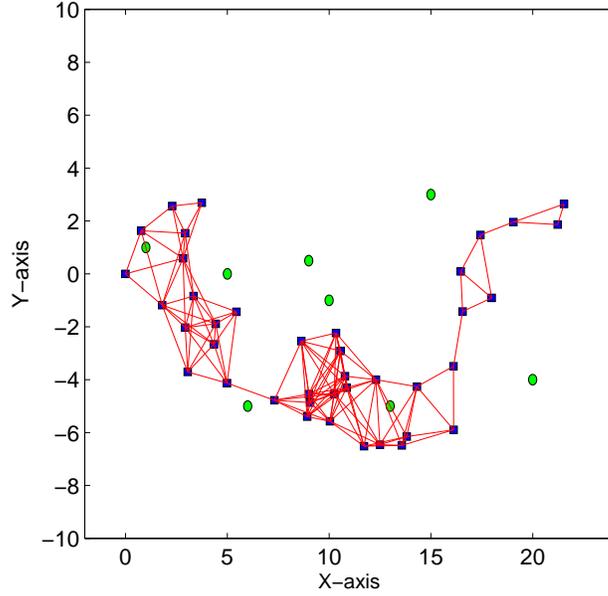


Figure 3-2. A connected initial graph with desired neighborhood in the workspace with static obstacles.

Each node is assumed to have a limited communication and sensing zone of  $R_c = 3$  m. The squares and dots denote the moving nodes and the static obstacles respectively, while the solid line connecting two nodes represents a communication link, indicating that the two nodes are located within each other's communication and sensing zone. The desired configuration is characterized by a circle with the inter-node distance of 2. The system is simulated for 600s with the step size of 0.1. The tuning parameter  $\alpha$  in (3-2) is set as  $\alpha = 1.5$ , and  $\delta_1 = \delta_2 = 0.4$  m in (3-5) and (3-6). Results in Fig. 3-3 indicate that the system finally converges to the desired configuration. Fig. 3-4 shows the inter-node distance between nodes converges to the desired value, and indicates that the communication links are maintained during the evolution (i.e., the distance between connected nodes is less than  $R_c = 3m$ ). To show the connectivity of the network during the evolution, the Fiedler eigenvalue of the graph Laplacian matrix is plotted in Fig. 3-5. Since the Fiedler eigenvalue is always positive, the graph is connected [93].

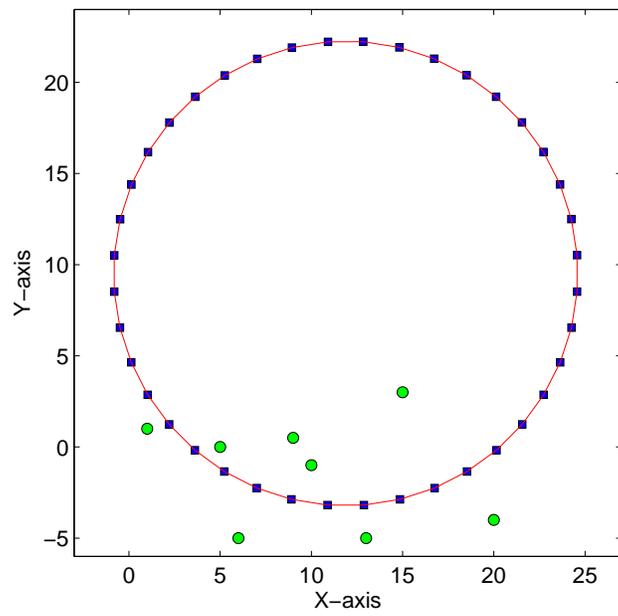


Figure 3-3. The achieved final configuration.

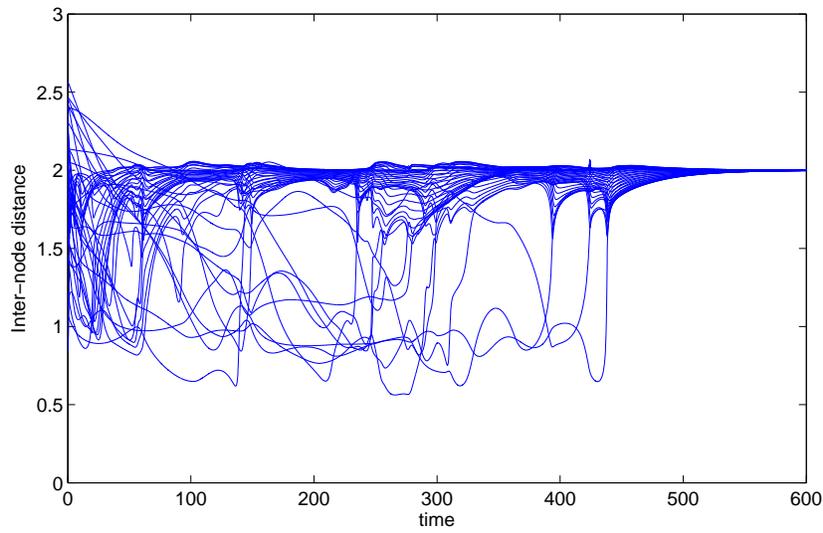


Figure 3-4. The inter-node distance during the evolution

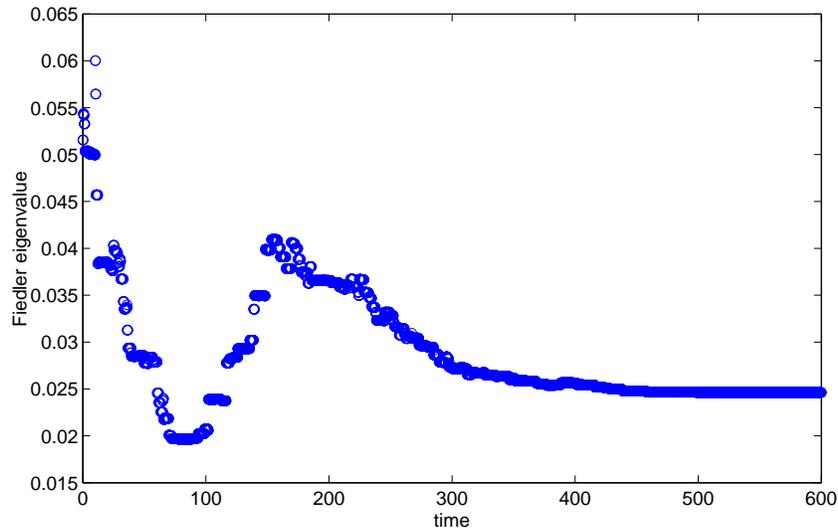


Figure 3-5. The plot of the Fiedler eigenvalue of the Laplacian matrix during the evolution. The circle indicates the Fiedler eigenvalue of the graph at each time instance.

### 3.5 Summary

Given an initial graph with a desired neighborhood, a navigation function based decentralized controller is developed to ensure the system asymptotically converges to the desired configuration while maintaining network connectivity and avoiding collisions with other agents and obstacles. A distinguishing feature of the developed approach is that the distributed agents achieve a coordinated global configuration without requiring radio communication. Future efforts are focused on enabling radio-silent navigation from an arbitrarily connected distributed network. Moreover, further efforts are required to eliminate Assumption 3.3 so that other obstacles or agents can be within the collision region of node  $i$  when node  $i$  is about to break the communication link. Likewise Assumption 3.4 becomes less practical as a point grows to a sphere in the presence of uncertainty, and as the workspace becomes more crowded. Future work is required to address the pervasive problem of obstacle avoidance in a cluttered workspace with uncertainty.

## CHAPTER 4

### NETWORK CONNECTIVITY PRESERVING FORMATION RECONFIGURATION FOR IDENTICAL AGENTS FROM AN ARBITRARY CONNECTED INITIAL GRAPH

A navigation function based decentralized method is developed in Chapter 3 to stabilize a group of agents in a desired formation while maintaining network connectivity. However, an assumption in Chapter 3 is that the initial topology is required to be a supergraph of the desired topology ensuring the agents are originally in a feasible interconnected state. Such initial graph assumption may limit its applications which require agents to achieve desired formations from an arbitrary initial graph or dynamically change the achieved formations to adapt to an uncertain environment. The focus of this chapter is to control a group of identical agents to achieve a desired formation from an arbitrarily connected initial condition, while preserving network connectivity during the motion. A novel network topology labeling algorithm developed in the work [52] is applied in this chapter to dynamically specify the neighborhood of each agent in the initial graph according to the desired formation, and determine the required movement for all nodes to achieve the desired formation. One distinguishing feature of this approach is that we do not wish to specify which nodes in the initial topology will take which positions in the final topology; rather, we only care that there is an agent in each position specified in the final topology. By modeling the network connectivity as an artificial obstacle, a navigation function based control scheme developed in our previous work of [94] is applied to guarantee the network connectivity by maintaining the neighborhood among agents determined by the prefix labeling algorithm, and ensure the convergence of all agents to the desired configuration with collision avoidance among agents using local information (i.e., local sensing and communication). An information flow is also proposed to specify the required movement for extra agents to their destination nodes. The information flow-based approach generally provides a path with more freedom for the motion of extra nodes without partitioning the network connectivity and allows communication links

to be formed or broken in a smooth manner without introducing discontinuity. Finally, convergence is proven using Rantzer's Dual Lyapunov Theorem [55].

#### 4.1 Problem Formulation

Consider a network composed of  $N$  agents in workspace  $\mathcal{F}$ , where agent  $i$  moves according to

$$\dot{q}_i = u_i, \quad i = 1, \dots, N \quad (4-1)$$

where  $q_i = [x_i \ y_i]^T \in \mathbb{R}^2$  denotes the position of agent  $i$  in a two dimensional (2D) plane, and  $u_i \in \mathbb{R}^2$  denotes the velocity of agent  $i$  (i.e., the control input). The workspace  $\mathcal{F}$  is assumed to be circular and bounded with radius  $R$ . Each agent in  $\mathcal{F}$  is assumed to be a point-mass with limited communication and sensing capability encoded by a local disk area. For simplicity and without loss of generality, the following development is based on the assumption that the sensing zone is the same as the communication zone, both with radius  $R_c$ . Two moving agents can communicate with each other if the relative distance is less than the radius  $R_c$ . All the agents are assumed to be identical with equal actuation capabilities. Each agent is assumed to have real-time knowledge of its own states.

Since each agent can only sense and communicate with other agents located within the distance  $R_c$ , the interaction among agents is modeled as an undirected graph  $\mathcal{G} = (\mathcal{V}, \mathcal{E}(t))$ , with  $\mathcal{V}$  denoting the index set of all nodes and the set of edges  $\mathcal{E} = \{(i, j) \in \mathcal{V} \times \mathcal{V} \mid d_{ij} \leq R_c\}$ , where node  $i$  and  $j$  represent agents located at position  $q_i$  and  $q_j$ , and  $d_{ij} \in \mathbb{R}^+$  is the distance between them, defined as  $d_{ij} = \|q_i - q_j\|$ . The edge  $(i, j)$  denotes a bidirectional communication link between node  $i$  and  $j$ , indicating that node  $i$  and  $j$  have access to the states of each other. The neighborhood of node  $i$ ,  $\mathcal{N}_i$ , (i.e., all the agents within the communication zone of agent  $i$ ), is given by  $\mathcal{N}_i = \{j, j \neq i \mid j \in \mathcal{V}, (i, j) \in \mathcal{E}\}$ , which is a time-varying set, since other nodes may enter or leave the communication region of node  $i$  at any time. The desired configuration is characterized by the specified relative position between nodes  $i$  and  $j \in \mathcal{N}_i^f$ , where  $\mathcal{N}_i^f$  denotes the set of neighbors for node  $i$  in  $\mathcal{G}_f$ , and the desired position  $q_{di}$  for node  $i$  is

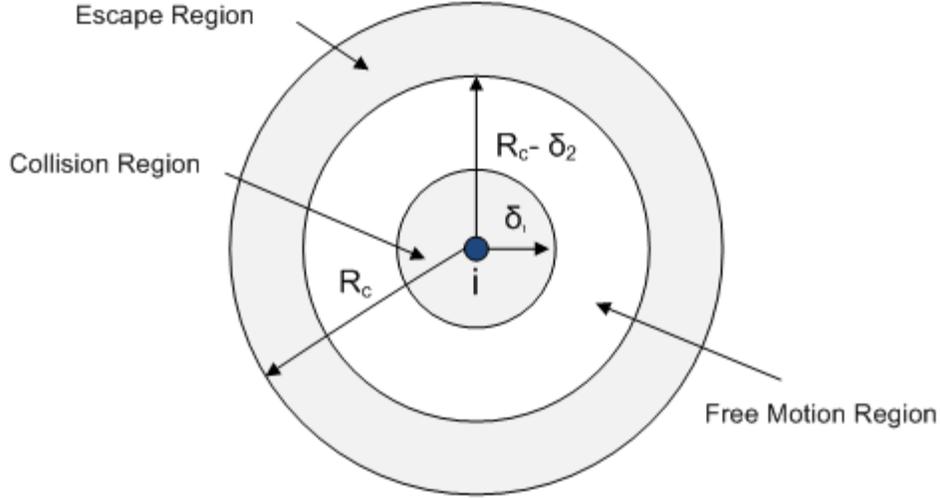


Figure 4-1. The small disk area with radius  $\delta_1$  denotes the collision region and the outer ring area denotes the escape regions for node  $i$ . The region in the sensing zone apart from collision and escape regions denotes the free-motion region.

defined as

$$q_{di} = \left\{ q_i \mid \|q_i - q_j - c_{ij}\|^2 = 0, j \in \mathcal{N}_i^f \right\}, \quad (4-2)$$

where  $c_{ij} \in \mathbb{R}^2$  represents the desired relative position between node  $i$  and  $j$ .

A collision region is defined for each agent  $i$  as a small disk area with radius  $\delta_1 < R_c$  around the agent  $i$ , such that any other agent  $j \in \mathcal{V}$  inside this region is considered as a potential collision with agent  $i$ . To ensure connectivity, an escape region for each agent  $i$  is defined as the outer ring of the communication area with radius  $r$ ,  $R_c - \delta_2 < r < R_c$ , where  $\delta_2 \in \mathbb{R}$  is a predetermined buffer distance. Edges formed with a node  $j \in \mathcal{N}_i$  in the escape region are in danger of breaking. Agent  $i$  moves with the constraint of avoiding a collision with other agents located in the collision region, and preventing a break in the communication link between agents located in the escape region. The collision and escape regions for agent  $i$  are shown in Fig. 4-1. The region within the sensing zone can be considered as the free-motion region where an agent can move freely.

Let  $\mathcal{G}_i$  denote the initial network topology and  $\mathcal{G}_f$  denote the desired final topology. The subsequent development is based on the following assumptions.

**Assumption 4.1.** *The initial graph associated with  $\mathcal{G}_i$  is connected and the initial positions do not coincide with some unstable equilibria (i.e., saddle points).*

**Assumption 4.2.**  *$\mathcal{G}_f$  is a tree, and all nodes in  $\mathcal{G}_i$  are assumed to have a knowledge of  $\mathcal{G}_f$  before applying the network topology labeling algorithms. The desired formation associated with  $\mathcal{G}_f$  is specified in advance and valid, which implies that the desired configuration is connected and will not lead to a collision or the desired configuration will not lead to a partitioned graph, i.e.,  $\delta_1 < \|c_{ij}\| < R_c - \delta_2$ .*

## 4.2 Formation Reorganization Strategy

To achieve a desired formation from an arbitrary initial graph while preserving network connectivity, the developed formation reorganization strategy has two stages: a networking-based labeling and routing algorithm over the network topology, and a potential field based motion control algorithm on the physical graph. Given an arbitrary initial graph, a labeling and routing algorithm is used to assign each agent a unique label, specify which node in the initial topology should take which position in the final topology, and determine how the initial topology can be transformed into the desired topology, all while preserving the network connectivity. After the network topology has been determined, a motion control algorithm is implemented to physically steer each agent toward a desired location based on the physical topology while maintaining network connectivity.

Specifically, the prefix labeling and routing algorithm subsequently described in Section 4.3 is first applied on the initial network graph to form a prefix tree by labeling the identical agents. A prefix tree is commonly called a trie [95]. A key observation is that, for arbitrary initial and desired final topologies, there are always spanning trees that eliminate loops while preserving connectivity. Before assigning prefix labels, the initial network topology may not be a tree. However, after assigning prefix labels, the network can be formed as a trie, and the length of the label corresponds to its depth in the trie. Once the trie is established, the initial trie topology can be reconfigured to a desired trie

topology by moving some agents. The novel idea is that the agents can be treated as packets that are then routed through the network. Hence, the agents can be moved toward its destination as routing a packet through the network. A distinguishing advantage of using prefix labeling and routing is that topology reconfiguration can be achieved from an arbitrary initial topology, since the labels, destinations and neighborhood for agents are dynamically determined, instead of being specified in advance like results such as [9, 39, 41, 45–48]. However, the prefix labeling and routing approach in Section 4.3 requires global communication for each agent to determine its own label and broadcast its label to other agents through the overall network. Since the agents are not physically moved in this stage, the prefix labeling procedure can be done in an off-line fashion for the given initial graph. Once the first stage is complete, the potential field based motion control algorithm developed in Section 4.4 is then applied to steer the agents to the desired formation while preserving network connectivity. Note that only local sensing and communication is used for the formation stabilization in the second stage.

### 4.3 Network Topology Labeling Algorithms

A prefix labeling and routing algorithm is developed in this section to label the agents with prefix, specify the neighborhood for each node in  $\mathcal{G}_i$ . Since some nodes (i.e., extra nodes) are required to be repositioned to achieve  $\mathcal{G}_f$ , the proposed algorithm also determines the destination and path for each extra node to achieve  $\mathcal{G}_f$  while preserving network connectivity.

#### 4.3.1 Basic Algorithm

A trie  $\mathcal{G}_t$  is generated from  $\mathcal{G}_i$  by randomly selecting a node in  $\mathcal{G}_i$  to be the root and letting the selected root assign a prefix label to each node in  $\mathcal{G}_i$  in breadth-first fashion [96]. For instance, in a simple form of prefix labeling, one node is elected to be the root. The neighbors of the root are labeled as children of the root in a prefix tree. Then those nodes label their children, and the process continues until each node has a unique

label<sup>1</sup>. The prefix label assigned to each node serves as its network address. To illustrate the prefix labeling algorithm, an example is provided Fig. 4-2, where the root is assigned the label 0. The children of the root are then assigned the labels {01, 02, 03} and {01, 02} in Fig. 4-2 (a) and Fig. 4-2 (b) respectively.

By identifying nodes in  $\mathcal{G}_t$  that do not match the desired topology  $\mathcal{G}_f$ , the node that is missing children is denoted as a *requesting node*, and the node whose label does not exist in  $\mathcal{G}_f$  is called an *extra node*. Each requesting node sends the root a message, M.Req, that includes a list of its missing children addresses. A copy of this message will also be stored at all nodes who are located along the path to the root. At the same time, each extra node also sends a message, M.Label, including its own label to the root. Once the root obtains all the messages from these nodes, the root will ask each extra node to move one-by-one starting from an extra node with the longest label (i.e., the extra node that is deepest in the trie). The extra node with the longest prefix label is moved first to preserve the network connectivity during the process. If an extra node is a parent of other extra nodes, the other extra node will be orphaned and thus may lose network connectivity if the parent node moves first.

In prefix routing, the extra node first finds out the destination node's prefix label, and then uses maximum prefix matching logic [49–51] to route themselves to the desired destination through the network. This extra node will check for cached M.Req messages in the nodes which are located along the way to the root for the missing node address. If there exists more than one missing node address, the extra node will decide to move to the closest missing node by comparing the prefix label of the missing node address and the current node address. Whenever this extra node reaches its parent requesting node

---

<sup>1</sup> Because of the loops in the graph, the labeling is not unique. That is, for a given graph, there may exist several different sets of labeling. However, in each individual set of labeling, each agent has a unique prefix label.

in  $\mathcal{G}_f$ , the requesting node will send a message, M.RCM, to the root confirming that it has received an extra node, and the extra node will be relabeled to take the role of the formerly missing node in the desired topology. This message also tells all the nodes along the path to the root to delete this missing node address from their cache. When the root obtains M.RCM, it will initiate the process again by asking the extra nodes at the next level in the trie to move. This process will continue until the desired network topology is achieved.

Fig. 4-2 is provided to illustrate the prefix routing algorithm. The node 03 and 031 in Fig. 4-2 (a) are extra nodes, since they do not exist in the Fig. 4-2 (b) by comparing the prefix labels in the initial and the desired topology in Fig. 4-2. To achieve the desired topology shown in Fig. 4-2 (b), node 031 is required to move first toward the node 01 through the path  $\{031, 03, 0, 01\}$ , since node 031 has the longest label among all the extra nodes. Once a new edge between node 01 and 031 is created, 031 is relabeled by 011, and following a similar process, node 03 then starts to move toward node 01 to fill the rest vacancy of 012 in Fig. 4-2 (b).

The time required to transition to the final topology can be reduced by allowing some extra nodes to move simultaneously. In Destination Assignment Algorithm, the root assigns each extra node a destination by sending them a message M.Dest, which includes the requesting node address. Pseudocode for Destination Assignment Algorithm is provided in Algorithm 4.1. In a tree topology, leaf nodes are those nodes who do not have children. Thus, leaf nodes can be repositioned without affecting network connectivity. If an extra node is a leaf node, it can move whenever it receives a message M.Dest, but other nodes have to wait for their children to move up the tree before the parent can move. An extra node that reaches the destination first will be immediately relabeled and forwarded by the requesting node to fulfill the desired network trie. If more than one extra node reach the destination requesting node at the same time, the requesting node will check the hop number of each extra node by comparing the extra node label with

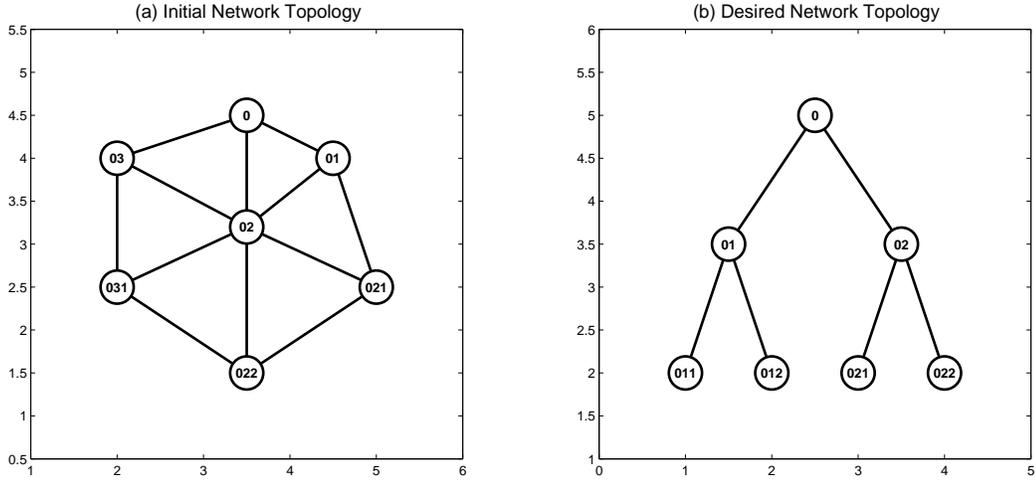


Figure 4-2. The example of an initially connected and desired graph topology, where the nodes denote the agent, and the lines connecting two nodes denote the available communication links. In Fig. 4-2 (a) and (b), the root is assigned the label 0. The children of the root are then assigned the labels  $\{01, 02, 03\}$  and  $\{01, 02\}$  in Fig. 4-2 (a) and (b) respectively. Other nodes such as  $\{021, 022, 031\}$  and  $\{011, 012, 021, 022\}$  are labeled by following a similar procedure.

its prefix. Then the requesting node will assign those nodes to its subtree to minimize the number of hops each node must travel. That is, nodes that have already traveled the largest number of hops will be assigned as children of the requesting node, whereas extra nodes that have traveled few hops will be assigned as the leaf nodes of the deepest part of the subtree.

### 4.3.2 Relabeling Algorithm

The performance of reorganizing the network topology is highly dependent on how the prefix labels are assigned in  $\mathcal{G}_i$ . To improve the performance of reorganization, Branch Relabeling (BR) and Neighbor Relabeling (NR) methods are developed to relabel the nodes in trie  $\mathcal{G}_t$ . Before applying these algorithms,  $\mathcal{G}_i$  is required to be prefix-labeled via the Basic Algorithm in the previous subsection, to form a trie  $\mathcal{G}_t$ . Pseudocode for Branch Relabeling and Neighbor Relabeling are provided in Algorithm 4.2 and Algorithm 4.3.

---

**Algorithm 4.1** Destination Assignment

---

```
1: procedure INPUT:(extranodes) ▷ extra node labels
2:   groups = GroupByPrefixLength(extranodes); ▷ Starting from the longest lengths group
3:   for  $G \in groups \ni G.length == \max(groups.length)$  do
4:     searchBackDepth = 1;
5:     for  $node \in G$  do
6:       node.DestinationAssigned = false;
7:     end for
8:     while  $\exists node \in G \ni node.DestinationAssigned == false$  do
9:       for  $node \in G \ni node.DestinationAssigned == false$  do
▷ Each time through this loop, search starting at ancestor that is
        searchBackDepth toward the root.
10:        parent = node;
11:        for  $i = 1$  to  $searchBackDepth$  do
12:          parent = GetNodeParent(parent);
13:        end for
14:        requestingNode = SearchSubtreeForClosestMissingNode(parent);
15:        if  $requestingNode \neq \emptyset$  then
16:          node.DestinationAddress = requestingNode;
17:          node.DestinationAssigned = true;
18:        end if
19:      end for
20:      searchBackDepth++;
21:    end while
22:    groups = groups - G;
23:  end for
24: end procedure
```

---

### 4.3.2.1 Branch Relabeling (BR) Algorithm

In the BR algorithm, the total amount of node movement required to achieve the desired network topology can be reduced by swapping the nodes prefix labels in two or more branches. Each leaf node sends a message including its label to the root. Once the root has the knowledge of all the node prefix labels in the network, starting from the root, nodes can then consider swapping the prefix label associated with two branches of descendants. In this work, branch relabeling is only applied at the root, since the root is most likely to have the largest impact on the amount of movement required to achieve the desired topology. An example BR algorithm is illustrated in Fig. 4-3, where the marked nodes denote the extra nodes, and the solid lines connecting two nodes indicate the required edges in the desired topology, shown in Fig. 4-2 (b). Before applying the BR algorithm, both node 03 and 031 are required to move all the way to node 01 to achieve the desired topology. After applying the BR algorithm, less movement is required since only node 03 is required to move.

---

**Algorithm 4.2** Branch Relabeling Algorithm

---

```
1: procedure INPUT:(Node)
                                     ▷ all node including label in the graph
2:   RootChild = GetRootChild(Node);
3:   RootChildSwap = AllSwap(RootNeighbor);
                                     ▷ obtain all swapping label pattern of all root neighbor
4:   for  $p \in$  RootChildSwap do
5:     Nodetemp = BRLabel(Node, p);
                                     ▷ Relabel all nodes in each branch according to p
6:     HopNum(p) = GetHopNum(Nodetemp);
                                     ▷ obtain the total hop number required for p
7:   end for
8:   p = MinHop(HopNum);
                                     ▷ obtain p achieving minimum total hop required
9:   Node = BRLabel(Node, p);
                                     ▷ Relabel each node according to p achieving minimum total hop required
10: end procedure
```

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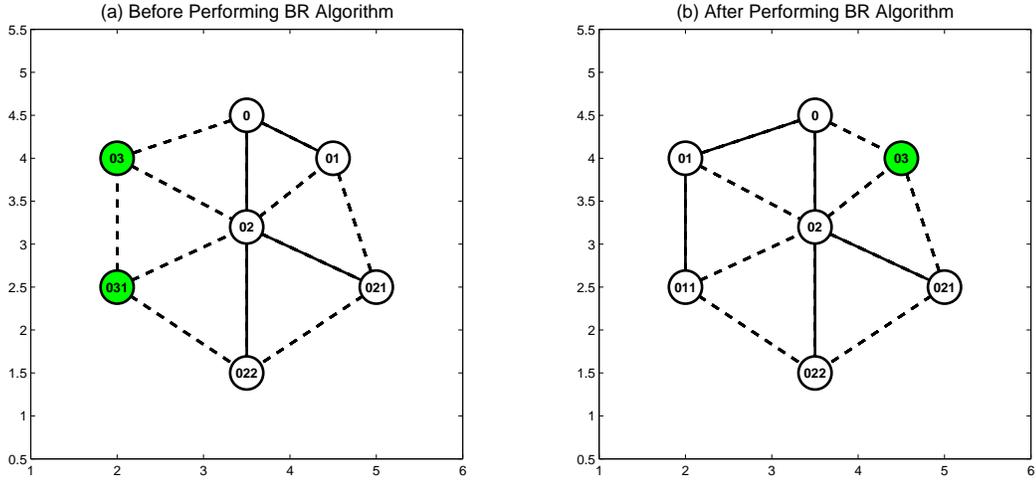


Figure 4-3. Fig (a) and (b) illustrates a graph before performing BR algorithm and after performing BR algorithm respectively, where the shaded nodes denote the extra nodes, the solid lines indicate the required edges in the desired topology in Fig. 4-2(b), and the dashed line indicate the available communication links but not required to maintain for the desired topology.

#### 4.3.2.2 Neighbor Relabeling (NR) Algorithm

The NR method is designed to relabel the extra nodes by exploiting additional connections that exist in  $\mathcal{G}_i$  to reduce the number of nodes required to move. All the nodes first check if they are extra nodes and reset the labels of extra nodes as null. Once the role of extra nodes is identified, all nodes that are missing children in  $\mathcal{G}_f$  will check if some of the extra nodes are their neighbors in  $\mathcal{G}_i$ . If so, the node that is missing children will relabel the neighboring extra node by sending it a message, M.Relabel. The process is repeated until no more relabeling is possible. Then, all remaining extra nodes will be labeled by their neighbors to form  $\mathcal{G}_t$ . An example NR algorithm is illustrated in Fig.4-4. Given an initial topology with prefix labeling as shown in Fig. 4-4 (a), two extra nodes are identified. After applying the NR algorithm, only one extra node is identified in Fig.4-4 (b).

For dense networks (in which the number of edges is high), NR may offer advantages over BR since NR can exploit the many network connections. In most cases, NR and BR can be combined to offer the greatest benefit across initial network topologies.

---

**Algorithm 4.3** Neighbor Relabeling Algorithm

---

```

1: procedure INPUT:(Node)
                                     ▷ all node including label in the graph
2:   RootChild = GetRootChild(Node);
3:   RootChildSwap = AllSwap(RootNeighbor);
                                     ▷ obtain all swapping label pattern of all root neighbor
4:   for  $p \in$  RootChildSwap do
5:     Nodetemp = BRLabel(Node, p);
                                     ▷ Relabel all nodes in each branch according to p
6:     HopNum(p) = GetHopNum(Nodetemp);
                                     ▷ obtain the total hop number required for p
7:   end for
8:   p = MinHop(HopNum);
                                     ▷ obtain p achieving minimum total hop required
9:   Node = BRLabel(Node, p);
                                     ▷ Relabel each node according to p achieving minimum total hop required
10: end procedure

```

---

## 4.4 Control Design

Section 4.3 describes how to determine the neighborhood for each node in  $\mathcal{G}_i$  according to the desired  $\mathcal{G}_f$ . This section will discuss about how to physically move all nodes to achieve the desired formation with topology  $\mathcal{G}_f$ , while maintaining network connectivity. Information flow is introduced to indicate the required communication for extra nodes. A potential field based decentralized control strategy is then developed to guide the extra nodes to their destinations, and ensure all nodes converge to the desired formation with collision avoidance among nodes while maintaining network connectivity.

### 4.4.1 Information Flow

Assume that the  $\mathcal{G}_i$  and  $\mathcal{G}_f$  are already prefix labeled. To achieve the desired  $c_{ij}$  in (4-2) for  $\forall i$  and  $j \in \mathcal{N}_i^f$ , a neighborhood between node  $i$  and  $j$  is required. Since the neighborhood in  $\mathcal{G}_i$  is specified according to  $\mathcal{G}_f$ , most nodes in  $\mathcal{G}_i$  start with desired neighbors (i.e., if two nodes are neighbors in the initial topology, they are also neighbors



of node  $i$  and  $j$ . Therefore, the following development is based on the assumption that the length of  $I_{ij}$  is at most two, which is not restrictive in the sense that an  $I_{ij}$  with path length greater than two can be partitioned into several connected partial path (i.e.,  $I_{ik_1}, I_{k_1k_2}, \dots, I_{k_nj}$  with  $k_1, \dots, k_n$  denoting the intermediate nodes of  $I_{ij}$ ) with the length of each section at most two. The extra node  $i$  can move in a step-by-step fashion by first approaching node  $k_1$ , then node  $k_2, \dots, k_n$ , until achieving its destination node  $j$ .

An information flow  $I_{ij}$  can be realized by several different paths, where the interest is not only maintaining the information flow  $I_{ij}$ , but also finding a short path to connect  $i$  and  $j$ . The mutual node is called the *relay node*, since it is used to pass information between node  $i$  and  $j$ . To indicate the freedom of motion that each agent can take without disconnecting the communication link, inspired by the work of [53] and [54], a locally measurable edge robustness term  $\delta_{mn}$  is defined as

$$\delta_{mn} = \frac{1}{2}(R_c - d_{mn}) \quad (4-3)$$

for any two immediate nodes  $m$  and  $n$  in the graph  $\mathcal{G}$  (i.e.,  $(m, n) \in \mathcal{E}$ ). The edge robustness  $\delta_{mn}$  is used to measure the robustness of the edge  $(m, n)$ , since node  $m$  and  $n$  will remain connected with each other, unless both of them are displaced by a distance of  $\delta_{mn}$ . Therefore, a larger  $\delta_{mn}$  indicates more freedom of motion. Due to node motion, some nodes may enter the communication zone of both node  $i$  and  $j$  at some time instant for an information flow  $I_{ij}$ , resulting in multiple options for the relay node. Using (4-3), the length of the two-edge path  $l_{ij}$  is represented as  $l_{ij} = d_{ir} + d_{rj} = 2R_c - 2(\delta_{ir} + \delta_{rj})$ , where  $\delta_{ir}$  and  $\delta_{rj}$  are the robustness of each communication link  $(i, r)$  and  $(r, j)$  computed from (4-3) respectively. Finding the shortest path for  $I_{ij}$  (i.e., minimizing  $l_{ij}$ ) is equal to maximizing the addition of  $\delta_{ir}$  and  $\delta_{rj}$ , since  $R_c$  is a constant. Path robustness is defined as  $\Delta_{I_{ij}} = \delta_{ir} + \delta_{rj}$ , and the goal is to minimize the time delay in communication by choosing the shortest path, and thereby maximizing the path robustness. Based on the

previous discussion, a relay node is determined by

$$r = \arg \max_{r \in \mathcal{N}_i \cap \mathcal{N}_j} \Delta I_{ij}, \quad (4-4)$$

where the maximum taken over the intersection of communication neighbors,  $\mathcal{N}_i \cap \mathcal{N}_j$ , aims to find a node providing the shortest path connecting node  $i$  and  $j$ . Motivation for choosing the addition of edge robustness as the path robustness, instead of choosing the minimum of the edge robustness (e.g., [53] and [54]) as the path robustness, is to avoid introducing a discontinuity in the control algorithm.

The information flow-based approach can be illustrated by an example, where the initial and desired topology are shown in Fig. 4-4 (b) and Fig. 4-2 (b) respectively. Since the labeling algorithm developed in Section 4.3 ensures that all nodes, except for extra nodes, start within the desired neighborhood (i.e., if two nodes are neighbors in the initial topology, they are also neighbors in the desired topology) in the initial topology, the nodes other than extra nodes only need to maintain connectivity of the desired neighborhood, which is illustrated by the labeled nodes and solid line in Fig. 4-4 (b) and Fig. 4-2 (b). For the extra node which is marked in Fig. 4-4 (b) as the shaded node, the information flow  $I_{ij}$  is used to indicate the required communication between the extra node and node 01. Since the information exchange can be realized by several paths in the communication graph (e.g., through the path  $\{0, 01\}$  or  $\{02, 01\}$  or other longer path), a short path can be identified by choosing a relay node that maximizes the path robustness in (4-4). A navigation function-based controller is then developed in the following section to ensure the connectivity of the required communication links, and ensures the system achieves the desired formation.

#### 4.4.2 Navigation Function-Based Control Scheme

Consider a decentralized navigation function candidate  $\varphi_i : \mathcal{F} \rightarrow [0, 1]$  for node  $i$  as

$$\varphi_i = \frac{\gamma_i}{(\gamma_i^\alpha + \beta_i)^{1/\alpha}}, \quad (4-5)$$

where  $\alpha \in \mathbb{R}^+$  is a tuning parameter,  $\gamma_i : \mathbb{R}^2 \rightarrow \mathbb{R}^+$  is the goal function, and  $\beta_i : \mathbb{R}^2 \rightarrow [0, 1]$  is a constraint function.

The goal function  $\gamma_i$  in (4-5) drives the system to a desired configuration, specified in terms of the desired relative pose with respect to the information neighbor  $j \in \mathcal{N}_i^f$ . The goal function  $\gamma$  is designed as

$$\gamma_i = \sum_{j \in \mathcal{N}_i^f} \|q_i - q_j - c_{ij}\|^2. \quad (4-6)$$

The gradient and Hessian matrix of  $\gamma_i$  are given as

$$\nabla_{q_i} \gamma_i = \sum_{j \in \mathcal{N}_i^f} 2(q_i - q_j - c_{ij}) \quad (4-7)$$

and

$$\nabla_{q_i}^2 \gamma_i = 2I_2 \zeta_i, \quad (4-8)$$

where  $I_2$  is the identity matrix in  $\mathbb{R}^{2 \times 2}$ , and  $\zeta_i \in \mathbb{R}^+$  denote the number of information neighbors in the set  $\mathcal{N}_i^f$ . Since the Hessian matrix of  $\gamma_i$  (4-8) is always positive definite, the goal function (4-6) has unique minimum, and the minimum is reached only when  $\nabla_{q_i} \gamma_i = 0$ , which implies that  $q_i$  and  $q_j$  achieves the desired relative pose from (4-7).

The constraint function  $\beta_i$  in (4-5) is designed for node  $i$  as

$$\beta_i = B_{i0} \prod_{j \in \mathcal{N}_i^f} b_{ij}^r \prod_{k \in \mathcal{N}_i^c \cup \mathcal{M}} B_{ik}, \quad (4-9)$$

to ensure connectivity of every information flow  $I_{ij}$ , and collision avoidance with the workspace boundary, adjacent nodes and moving obstacles at each time instant. In (4-9),  $b_{ij}^r \triangleq b(q_i, q_r) : \mathbb{R}^2 \rightarrow [0, 1]$  ensures connectivity of an information flow  $I_{ij}$  (i.e., guarantees

that the relay node  $r$  will always be connected to node  $i$ ) and is designed as

$$b_{ij}^r = \begin{cases} 1 & d_{ir} \leq R_c - \delta_2 \\ -\frac{1}{\delta_2^2}(d_{ir} + 2\delta_2 - R_c)^2 \\ + \frac{2}{\delta_2}(d_{ir} + 2\delta_2 - R_c) & R_c - \delta_2 < d_{ir} < R_c \\ 0 & d_{ir} \geq R_c. \end{cases} \quad (4-10)$$

Node  $i$  is aware of  $\delta_{rj}$  and  $\mathcal{N}_j$  in (4-4) through communication with node  $j$ . Thus, the node  $r$  can be determined locally from (4-4). Also in (4-9),  $B_{ik} \triangleq B(q_i, q_k) : \mathbb{R}^2 \rightarrow [0, 1]$ , for point  $k \in \mathcal{N}_i$ , ensures that node  $i$  is repulsed from all nodes located within its sensing zone to prevent a collision, and is designed as

$$B_{ik} = \begin{cases} -\frac{1}{\delta_1^2}d_{ik}^2 + \frac{2}{\delta_1}d_{ik} & d_{ik} < \delta_1 \\ 1 & d_{ik} \geq \delta_1. \end{cases} \quad (4-11)$$

Similarly, the function  $B_{i0}$  in (4-9) is used to model the potential collision of node  $i$  with the workspace boundary, where the positive scalar  $B_{i0} \in \mathbb{R}$  is designed similar to  $B_{ik}$  with the replacement of  $d_{ik}$  by  $d_{i0}$ , where  $d_{i0} \in \mathbb{R}^+$  is the relative distance of node  $i$  to the workspace boundary defined as  $d_{i0} = R - \|q_i\|$ .

Based on the definition of the navigation function candidate, a decentralized controller for each node is designed as

$$u_i = -K_i \nabla_{q_i} \varphi_i, \quad (4-12)$$

where  $K_i$  is a positive gain, and  $\nabla_{q_i} \varphi_i$  is the gradient of  $\varphi_i$  with respect to  $q_i$ , given as

$$\nabla_{q_i} \varphi_i = \frac{\alpha \beta_i \nabla_{q_i} \gamma_i - \gamma_i \nabla_{q_i} \beta_i}{\alpha(\gamma_i^\alpha + \beta_i)^{\frac{1}{\alpha}+1}}. \quad (4-13)$$

In (4-10) and (4-11),  $b_{ij}^r$  and  $B_{ik}$  are both designed to be continuous and differentiable functions in  $(0, R_c)$ , with  $b_{ij}^r$  achieving the minimum when the communication link  $(i, r)$  is about to be broken (e.g.,  $d_{ir} = R_c$ ) and  $B_{ik}$  achieves the minimum when nodes  $i$  and  $k$  are about to collide. The constraint function only takes effect whenever node  $i$

has the potential to break an existing communication link or collide with other nodes. The gradient of  $b_{ij}^r$  and  $B_{ik}$  are the zero vector in the free motion region, (i.e., the interval of  $(\delta_1, R_c - \delta_2)$ ), as shown in Fig. 4-1, which indicates that node  $i$  is only driven by its goal function (4-6) to form the desired relative pose with node  $j \in \mathcal{N}_i^f$  from (4-12) and (4-13). If node  $i$  dynamically builds new communication links or breaks existing links to the agents within the free motion region, the controller is still continuous from (4-13), since  $\nabla_{q_i}\beta_i = 0$  and  $\beta_i = 1$  in the free motion region. In contrast with the discontinuity introduced in the switching topology in current literature (see e.g., [40]), this highlighted feature enables a smooth transition between node  $i$  and other connected nodes.

#### 4.4.3 Connectivity and Convergence Analysis

The previous development indicates that  $\mathcal{G}$  is connected if the information flow  $I_{ij}$  is maintained in  $\mathcal{G}$ . The following proof indicates that the controller in (4-12) can guarantee connectivity of information flow  $I_{ij}$  in  $\mathcal{G}$ .

**Proposition 4.1.** *For any information flow  $I_{ij}$  with node  $r$  as the relay node, the control law (4-12) will guarantee that  $I_{ij}$  is maintained all the time, that is node  $i$  and  $j$  are connected in a communication path in  $\mathcal{G}$ .*

*Proof.* An information flow  $I_{ij}$  is realized in the communication graph  $\mathcal{G}$  by a path from node  $i$  to node  $j$  through a mutual node  $r$ . From the definition of a relay node,  $r \in \mathcal{N}_i \cap \mathcal{N}_j$ , which means node  $r$  is located in the communication zone of both  $i$  and  $j$ . To show that the edge  $(i, r)$  is maintained under the control law (4-12), consider node  $i$  located at a point  $q_0 \in \mathcal{F}$  that causes  $b_{ij}^r = 0$ , which indicates that node  $i$  is about to disconnect with node  $r$ . Since  $b_{ij}^r = 0$ ,  $\beta_i = 0$  from (4-9), the navigation function achieves its maximum value from (4-5). Since  $\varphi_i$  is maximized at  $q_0$ , no open set of initial conditions can be attracted to  $q_0$  under the negated gradient control law designed in (4-12). Therefore, the communication link between node  $i$  and  $r$  is maintained by the controller (4-12). Following the same procedure, the edge  $(r, j)$  can be maintained by a similar control applied to node  $j$ . Due to the motion of the nodes, some other node

$k$  may provide a shorter path connecting node  $i$  and  $j$  than node  $r$  from some time instant. When this occurs, it is reasonable to create a new path from node  $i$  to node  $j$  through node  $k$  to maintain the information flow  $I_{ij}$ . The relay node  $k$  can be determined according to (4-4) and does not introduce a discontinuity. Node  $k$  can be switched from node  $r$  in the free motion region of both node  $i$  and  $j$ . Following the analysis above, the connectivity of the new path can also be guaranteed.  $\square$

#### 4.4.4 Convergence Analysis

Our previous work in [48] proves that the proposed  $\varphi_i$  in (4-5) is a qualified navigation function, which guarantees convergence of the system to the desired configuration. From [48], the control law (4-12) ensures that almost all initial conditions are either brought to a saddle point or to the unique minimum  $q_{di}$  on a compact connected manifold with boundary, as long as the tuning parameter  $\alpha$  in (4-5) satisfies that  $\alpha > \max\{1, \Gamma(\varepsilon)\}$ , where  $\Gamma(\varepsilon)$  is developed in [48]. The following development uses Rantzer's Dual Lyapunov Theorem [55] to show that the undesired critical points (i.e., saddle points) are all measure zero, and the system can only converge to the unique minimum  $q_{di}$ . For the bounded workspace in this work, a variation of Rantzer's Dual Lyapunov Theorem is stated as [28]:

**Theorem 4.1.** *Suppose  $x^* = 0 \in S$  where  $S$  is an open, positively invariant, bounded subset of  $\mathbb{R}^n$  is a stable equilibrium point for  $\dot{x}(t) = f(x(t))$ , where  $f \in C^1(S, \mathbb{R}^n)$ ,  $f(0) = 0$ . Furthermore, suppose there exists a function  $\rho \in C^1(S - \{0\}, \mathbb{R})$  such that  $\rho(x)f(x)/\|x\|$  is integrable on  $\{x \in S : \|x\| \geq 1\}$  and*

$$[\nabla \cdot (f\rho)] > 0 \text{ for almost all } x \in S. \quad (4-14)$$

*Then, for almost all initial states  $x(0) \in S$ , the trajectory  $x(t)$  exists for  $t \in [0, \infty)$  and tends to zero as  $t \rightarrow \infty$ .<sup>2</sup>*

---

<sup>2</sup> For a function  $f : \mathbb{R}^n \rightarrow \mathbb{R}^n$ , the notation of divergence is defined as  $\nabla \cdot f = \frac{\partial f_1}{\partial x_1} + \dots + \frac{\partial f_n}{\partial x_n}$ .

Theorem 4.1 requires  $x^* = 0 \in S$  to be a stable equilibrium point. From (4-2) and (4-6), the goal function evaluated at the desired point is  $\gamma_i|_{q_{di}} = 0$ , and  $\nabla_{q_i}\gamma_i|_{q_{di}} = 0$  from (4-7), which can be used to conclude that  $\nabla_{q_i}\varphi_i|_{q_{di}} = 0$  from (4-13). Thus, the desired point  $q_{di}$  in the workspace  $\mathcal{F}$  is a critical point of  $\varphi_i$ . Using the facts that  $\gamma_i|_{q_{di}} = 0$  and  $\nabla_{q_i}\gamma_i|_{q_{di}} = 0$  and the Hessian of  $\gamma_i$  is  $\nabla_{q_i}^2\gamma_i = 2\zeta_i I_2$  from (4-8), the Hessian of  $\varphi_i$  evaluated at  $q_{di}$  is given by  $\nabla_{q_i}^2\varphi_i|_{q_{di}} = 2\beta_i^{-\frac{1}{\alpha}} I_2\zeta_i$ . The constraint function  $\beta_i > 0$  at the desired configuration by Assumption 2, and  $\zeta_i$  is a positive number. Hence, the Hessian of  $\varphi_i$  evaluated at  $q_{di}$  is positive definite, and the navigation function  $\varphi_i$  is minimized at  $q_{di}$ .

**Proposition 4.2.** *The closed-loop kinematics of system (4-1) with the controller (4-12) are given by  $\dot{\mathbf{q}} = f(\mathbf{q})$ , where  $\mathbf{q}$  denotes the stacked states of each node as  $\mathbf{q} = [q_1^T \cdots q_N^T]^T$  and  $f(\mathbf{q}) = [f_1^T \cdots f_N^T]$  with  $f_i^T = -K_i \nabla_{q_i} \varphi_i$  for  $\forall i \in \mathcal{N}$ . Consider the system  $\dot{\mathbf{q}} = f(\mathbf{q})$  for  $\forall i \in \mathcal{N}$ , and a density function as  $\rho = -\varphi$ , where  $\varphi = \sum_{i=1}^N \varphi_i$  in Theorem 1. If there exists an  $\varepsilon' > 0$  such that (4-14) is satisfied, the undesired critical points are sets of measure zero from Theorem 1, provided  $\alpha > \max\{1, \Gamma(\varepsilon), \varepsilon'\}$  at any saddle points, where  $\alpha$  is a parameter in the navigation function (4-5).*

*Proof.* The function  $\rho$  is defined for all points in the workspace other than the desired equilibrium  $q_{di}$ , and each  $\varphi_i$  is  $C^2$  and takes a value in  $[0, 1]$ . Thus both the function  $\varphi$  and its gradient are bounded functions in the workspace, which indicates that the integrability condition in Theorem 1 is fulfilled. From the divergence criterion,  $\nabla \cdot (f\rho) = (\nabla\rho)^T f + \rho \nabla \cdot (f)$ , and from the definition of a critical point,  $\nabla_{q_i}\varphi_i = 0$ . Hence,  $f_i^T = -K_i \nabla_{q_i}\varphi_i = 0$  for  $\forall i \in \mathcal{N}$ , which indicates that  $f = 0$ , and  $\nabla \cdot (f\rho)$  can be simplified as

$$\nabla \cdot (f\rho) = \varphi \sum_{i=1}^N K_i \left( \frac{\partial^2 \varphi_i}{\partial x_i^2} + \frac{\partial^2 \varphi_i}{\partial y_i^2} \right). \quad (4-15)$$

Since  $\varphi$  are positive at undesired critical points from (4-5), and  $K_i$  is a positive gain, a sufficient condition for (4-15) to be strictly positive is  $\frac{\partial^2 \varphi_i}{\partial x_i^2} + \frac{\partial^2 \varphi_i}{\partial y_i^2} > 0$ . Using (4-13),  $\frac{\partial^2 \varphi_i}{\partial x_i^2}$

and  $\frac{\partial^2 \varphi_i}{\partial y_i^2}$  are computed as

$$\frac{\partial^2 \varphi_i}{\partial x_i^2} = \frac{\left( \frac{\partial \beta_i}{\partial x_i} \frac{\partial \gamma_i}{\partial x_i} + \beta_i \frac{\partial^2 \gamma_i}{\partial x_i^2} - \frac{1}{\alpha} \frac{\partial \beta_i}{\partial x_i} \frac{\partial \gamma_i}{\partial x_i} - \frac{\gamma_i}{\alpha} \frac{\partial^2 \beta_i}{\partial x_i^2} \right)}{(\gamma_i^\alpha + \beta_i)^{\frac{1}{\alpha} + 1}} \quad (4-16)$$

$$\frac{\partial^2 \varphi_i}{\partial y_i^2} = \frac{\left( \frac{\partial \beta_i}{\partial y_i} \frac{\partial \gamma_i}{\partial y_i} + \beta_i \frac{\partial^2 \gamma_i}{\partial y_i^2} - \frac{1}{\alpha} \frac{\partial \beta_i}{\partial y_i} \frac{\partial \gamma_i}{\partial y_i} - \frac{\gamma_i}{\alpha} \frac{\partial^2 \beta_i}{\partial y_i^2} \right)}{(\gamma_i^\alpha + \beta_i)^{\frac{1}{\alpha} + 1}}. \quad (4-17)$$

Observing that  $\frac{\partial^2 \varphi_i}{\partial x_i^2}$  and  $\frac{\partial^2 \varphi_i}{\partial y_i^2}$  has similar structure, it suffices to show that  $\frac{\partial^2 \varphi_i}{\partial x_i^2} > 0$  for  $\forall i \in \mathcal{N}$ , since the same results can be derived for  $\frac{\partial^2 \varphi_i}{\partial y_i^2}$ . Since  $\gamma_i$  and  $\beta_i$  are positive from (4-6) and (4-9), and can not be zero simultaneously from Assumption 2, the positivity of (4-16) can be proven by showing that the numerator of the right side of (4-16) is positive. Using the fact that  $\frac{\partial \beta_i}{\partial x_i} = \frac{\alpha \beta_i}{\gamma_i} \frac{\partial \gamma_i}{\partial x_i}$  at a critical point, the following expression can be obtained from (4-16):

$$C_1 \alpha^2 + C_2 \alpha + C_3 > 0. \quad (4-18)$$

where,  $C_1 = \frac{\beta_i}{\gamma_i} \left( \frac{\partial \gamma_i}{\partial x_i} \right)^2$ ,  $C_2 = \frac{\beta_i}{\gamma_i} \left( \frac{\gamma_i \partial^2 \gamma_i}{\partial x_i^2} - \left( \frac{\partial \gamma_i}{\partial x_i} \right)^2 \right)$  and  $C_3 = -\frac{\gamma_i \partial^2 \beta_i}{\partial x_i^2}$ . Note that  $\beta_i = 0$  indicates  $\varphi_i$  achieves its maximum from (4-5). However, since the set of initial conditions is open, and no open set of initial conditions can be attracted to the maxima of  $\varphi_i$  along the negative gradient motion  $-K_i \nabla_{q_i} \varphi_i$  [9], then  $\beta_i \neq 0$ . In addition,  $\gamma_i$  is evaluated at the undesired critical points (i.e., except the  $q_{di}$ ), so  $\gamma_i \neq 0$  and  $\frac{\partial \gamma_i}{\partial x_i} \neq 0$  from (4-6) and (4-7). To satisfy the condition in (4-18), two cases are considered for

$$C_1 \alpha^2 + C_2 \alpha + C_3 = 0. \quad (4-19)$$

Case 1: No solution of  $\alpha$  exists for (4-19): Since  $\frac{\beta_i}{\gamma_i} \left( \frac{\partial \gamma_i}{\partial x_i} \right)^2 > 0$ , which means  $\alpha$  can be arbitrary value. Note that  $\alpha$  is a positive gain in (4-5). Hence, as long as  $\alpha > 0$ , the condition in (4-18) is valid in Case 1.

Case 2: Two solutions,  $S_1$  and  $S_2$ , exist for  $\alpha$  in (4-19): In this case, the condition in (4-18) is satisfied as long as  $\alpha > \max \{S_1, S_2, 0\}$ . Combining Case 1 and Case 2, indicates that if  $\alpha > \max \{1, \Gamma(\varepsilon), \varepsilon'\}$ , where  $\varepsilon'$  is defined as  $\varepsilon' = \max \{S_1, S_2, 0\}$ ,

all saddle points are measure zero, and the system will only converge to the desired configuration. □

## 4.5 Simulation

In this section, the proposed strategy is simulated for a group of 10 nodes to achieve a desired “letter A” formation shown in Fig. 4-5 (a) from an arbitrarily connected initial graph. In Fig. 4-5 (a), the circles represent the nodes and the solid lines indicate the desired communication links between connected nodes, and the prefix labeled desired graph is shown in Fig. 4-5 (b) after applying the labeling algorithms in Section 4.3.

An arbitrary connected initial graph is generated in Fig. 4-7 (a). Note that the initial topology in Fig. 4-7 (a) is not a supergraph of the desired topology in Fig. 4-5 (a). The existing results in [9, 11, 48] are not applicable to the current example. When applying the network topology labeling algorithm described in Section 4.3, the initial topology can be labeled as in Fig. 4-7 (b). Comparing Fig. 4-5 (b) and Fig. 4-7 (b), all nodes have desired neighbors except two nodes: node 011 is missing a child, and node 011111 does not exist in Fig. 4-5 (b). Node 011111 is identified as an extra node and required to move up the trie toward its destination node 011 to fill the vacancy of node 0112. Applying the control strategy developed in Section 4.4, the desired formation is achieved as shown in Fig. 4-7.

## 4.6 Summary

Cooperative formation control for a group of identical agents with limited sensing and communication capabilities is achieved in this work. Through the use of a prefix labeling strategy, the initial topology assumption (i.e., required to be a supergraph the desired topology) presented in most previous work is relaxed, which enables identical agents to achieve a desired formation from any connected initial graph, and dynamically change their formation to adapt to an uncertain environment. A decentralized control method using local information is developed to guarantee the agents cooperatively converge to the desired formation without disconnecting the underlying network graph with collision avoidance among agents. Future work will focus on extending the proposed approach to

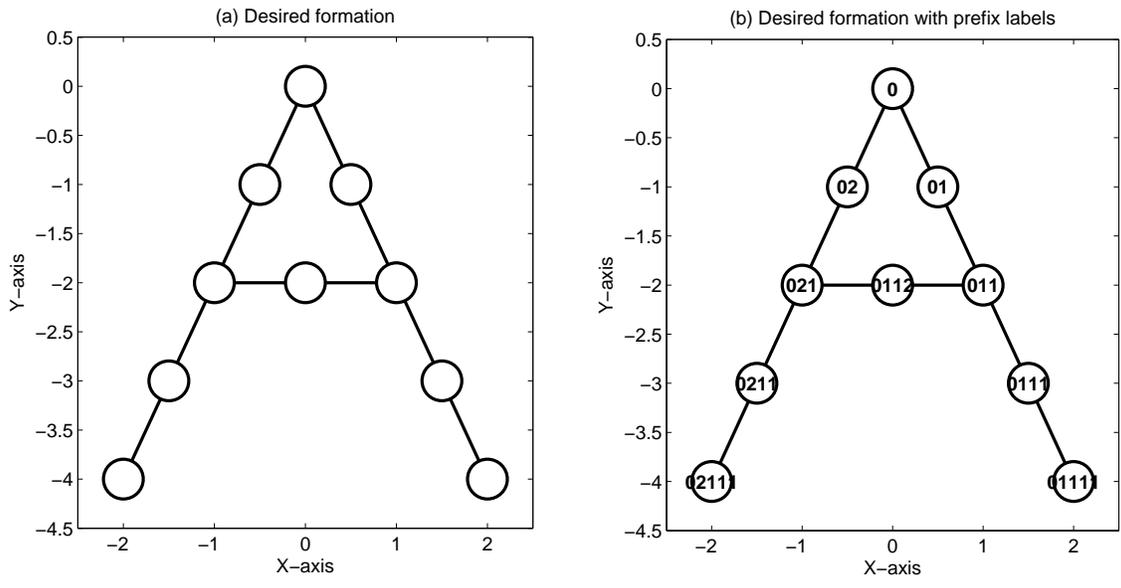


Figure 4-5. The desired formation is characterized by a "letter A", where the nodes denote the agent, and the lines connecting two nodes denote the available communication links. Fig (a) shows the desired formation, while Fig (b) shows how Fig (a) is labeled by prefix using the proposed prefix labeling algorithm.

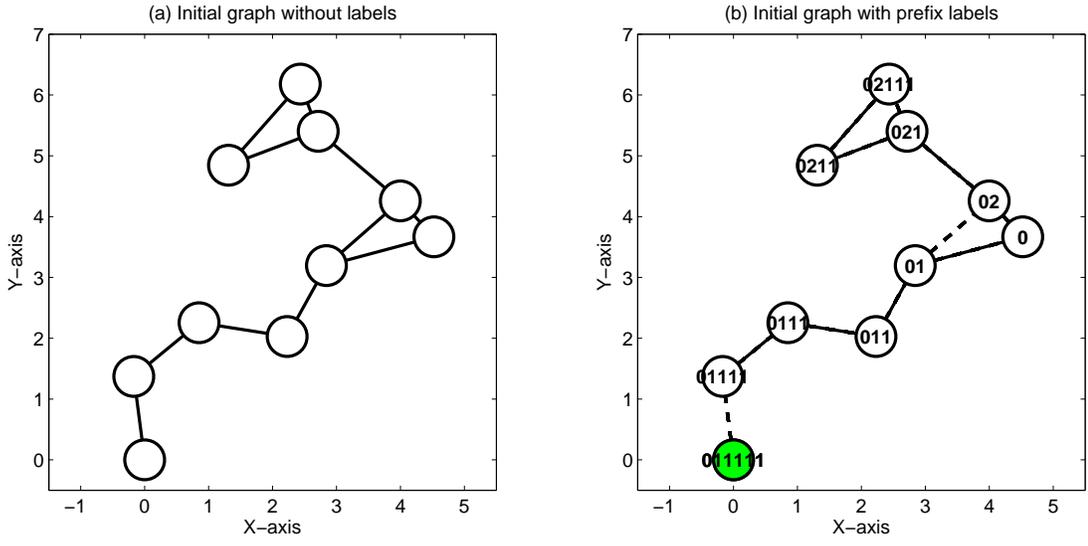


Figure 4-6. Fig (a) shows a randomly generated connected initial graph, while Fig (b) shows how the initial graph is labeled by prefix. In Fig (b), the solid lines indicate the desired neighborhood, and the marked node 011111 is identified as an extra node.

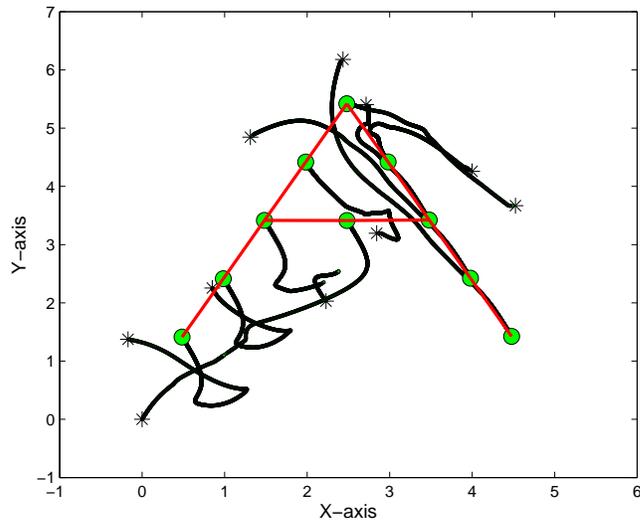


Figure 4-7. The trajectories of all nodes to achieve the desired formation, with "\*" denoting their initial positions and circles denoting their final positions.

the application of non-homogeneous agents, and optimizing the inter-agent communication during the operation.

## CHAPTER 5

### ENSURING NETWORK CONNECTIVITY FOR NONHOLONOMIC ROBOTS DURING DECENTRALIZED RENDEZVOUS

Artificial potential field based controllers are developed in Chapter 2-4 to perform desired tasks while preserving the network connectivity during the mission. However, only linear models of motion are taken into account in Chapter 2-4, i.e., the first order integrator. The focus of this chapter is to design decentralized controllers for a group of wheeled mobile robots with nonholonomic constraints. Based on our previous work in [60], a decentralized continuous time-varying controller, using only local sensing feedback from its one-hop neighbors, is designed in [97] to stabilize a group of wheeled mobile robots with nonholonomic constraints at a specified common setpoint with a desired orientation. One feature of the controller developed in this chapter is that it considers a cooperative objective of maintaining the network connectivity during network regulation. Another feature of the decentralized controller is that, using local sensing information, no inter-agent communication is required (i.e., communication-free global decentralized group behavior). That is, network connectivity is maintained so that the radio communication is available when required for various tasks, but communication is not required for navigation. Using the navigation function framework, the multi-robot system is guaranteed to maintain connectivity and be stabilized at a common destination with a desired orientation without being trapped by local minima. Moreover, this result can be extended to other applications by replacing the objective function in the navigation function to accommodate different tasks, such as formation control, flocking, and other applications.

#### 5.1 Problem Formulation

Consider a networked multi-robot system composed of  $N$  Wheeled Mobile Robots (WMRs) operating in a workspace  $\mathcal{F}$ , where  $\mathcal{F}$  is a bounded disk area with radius  $R_w$ , and  $\partial\mathcal{F}$  denotes the boundary of  $\mathcal{F}$ . In the workspace  $\mathcal{F}$ , each robot moves according to

the following nonholonomic kinematics:

$$\dot{q}_i = \begin{bmatrix} \cos \theta_i & 0 \\ \sin \theta_i & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_i(t) \\ \omega_i(t) \end{bmatrix}, \quad i = 1, \dots, N \quad (5-1)$$

where  $q_i(t) \triangleq \begin{bmatrix} p_i^T(t) & \theta_i(t) \end{bmatrix}^T \in \mathbb{R}^3$  denotes the states of robot  $i$ , with  $p_i \triangleq \begin{bmatrix} x_i(t) & y_i(t) \end{bmatrix}^T \in \mathbb{R}^2$  denoting the position of robot  $i$ , and  $\theta_i \in (-\pi, \pi]$  denoting its orientation with respect to the global coordinate frame in the workspace  $\mathcal{F}$ . In (5-1),  $v_i(t), \omega_i(t) \in \mathbb{R}$  are the control inputs, representing the linear and angular velocity of robot  $i$ , respectively.

Assume that each robot has a limited communication and sensing capability encoded by a disk area with radius  $R_c$  and  $R_s$  respectively, and  $R_c \geq R_s$ , which ensures that two robots are able to communicate with each other as long as they can sense each other. For simplicity and without loss of generality, it is assumed that the sensing area coincides with the communication area (i.e.,  $R_c = R_s = R$ ) in the following development. Two moving robots can communicate with and sense each other as long as they stay within a distance of  $R$ . Further, all the robots are assumed to have equal actuation capabilities. The interaction among the WMRs is modeled as an undirected graph  $\mathcal{G}(t) = (\mathcal{V}, \mathcal{E}(t))$ , where  $\mathcal{V} = \{1, \dots, N\}$  denotes the set of nodes, and  $\mathcal{E}(t) = \{(i, j) \in \mathcal{V} \times \mathcal{V} \mid d_{ij} \leq R\}$  denotes a set of time-varying edges. In graph  $\mathcal{G}(t)$ , each node  $i \in \mathcal{V}$  represents a robot located at a position  $p_i$ , and an undirected edge  $(i, j) \in \mathcal{E}$  exists between node  $i$  and  $j$  in  $\mathcal{G}(t)$  if their relative distance  $d_{ij} \triangleq \|p_i - p_j\| \in \mathbb{R}^+$  is less than  $R$ , which indicates that node  $i$  and  $j$  are able to access the states (i.e., position and orientation) of each other through local sensing and information exchange. The neighbor set of node  $i$  is denoted as  $\mathcal{N}_i = \{j \mid (i, j) \in \mathcal{E}\}$ , which includes the nodes that can be sensed and reached for communication. Since the graph  $\mathcal{G}(t)$  is undirected,  $i \in \mathcal{N}_j \iff j \in \mathcal{N}_i$  for  $\forall i, j \in \mathcal{V}$ ,  $i \neq j$ . Due to the limited sensing and communication capabilities, node  $i$  only knows the

states of those nodes within its sensing range and can only communicate with nodes within its communication range. Once node  $j$  moves out of the sensing and communication zone of node  $i$ , node  $i$  will no longer share information with node  $j$  directly, which may lead to mission failure. Hence, to complete desired tasks, maintaining connectivity of the underlying graph is necessary.

The main objectives in this chapter are to derive a set of distributed controllers using only local information (i.e., the states of the other robots within its sensing area) to lead the group of WMRs to rendezvous at a common destination  $p^*$  with a desired orientation  $\theta_i^*$ , i.e.,  $q_i^* = \begin{bmatrix} (p^*)^T & \theta_i^* \end{bmatrix}^T \forall i$  in the workspace  $\mathcal{F}$ , while guaranteeing the underlying graph  $\mathcal{G}(t)$  remains connected during the system evolution, provided the given initial graph is connected. To achieve these goals, the following assumptions are required in the subsequent development.

**Assumption 5.1.** *The initial graph  $\mathcal{G}$  is connected, and those initial conditions do not coincide with unstable equilibria (i.e., saddle points).*

**Assumption 5.2.** *The destination  $p^*$  and desired orientation  $\theta_i^*$  is known for each robot and achievable, which indicates that the destination will not meet any constraints, i.e., coincide with the workspace boundary, or lead to the partition of the underlying graph.*

## 5.2 Control Design

### 5.2.1 Dipolar Navigation Function

Artificial potential field-based methods that use attractive and repulsive potentials have been widely used to control multi-robot systems. Due to the existence of local minima when attractive and repulsive force are combined, robots can be trapped by local minima and are not guaranteed to reach the global minimum of the potential field. A navigation function is a particular category of potential functions where the potential field does not have local minima and the negative gradient vector field of the potential field guarantees convergence to a desired destination, along with possible collision avoidance. Formally, a navigation function is defined as:

**Definition 5.1.** [30] [29], Let  $\mathcal{F} \subset E^n$  be a compact connected analytic manifold with boundary. A map  $\varphi : \mathcal{F} \rightarrow [0, 1]$  is a Navigation Function, if it is: 1) smooth on  $\mathcal{F}$  (at least a  $\mathcal{C}^2$  function); 2) admissible on  $\mathcal{F}$ , (uniformly maximal on  $\partial\mathcal{F}$  and constraint boundary); 3) polar on  $\mathcal{F}$ , ( $q_d$  is a unique minimum); and 4) a Morse function, (critical points of the navigation function are non-degenerate).

Specifically, property 2) establishes that the generated trajectories are collision-free, since the resulting vector field is transverse to the boundary of  $\mathcal{F}$ , while property 3) indicates that, using a polar function on a compact connected manifold with boundary, all initial conditions are either brought to a saddle point or to the unique minimum  $q_d$ . The last property ensures that the initial conditions that bring the system to saddle points are sets of measure zero [30]. Given this property, all initial conditions away from sets of measure zero are brought to the unique minimum.

The navigation function introduced in [30] and [29] ensures global convergence of the closed-loop system; however, the approach is not suitable for nonholonomic systems, since the feedback law generated from the gradient of the navigation function can lead to undesired behavior. To overcome the undesired behaviors, the original navigation function was extended to a Dipolar Navigation Function in [58] and [92], where the flow lines created in the potential field resemble a dipole, so that the flow lines are all tangent to the desired orientation at the origin and the vehicle can achieve the desired orientation. One example of the dipolar navigation is shown in Fig. 5-1, where the potential field has a unique minimum at the destination (i.e.,  $p^* = [0, 0]^T$  and  $\theta^* = 0$ ), and achieves the maxima at the workspace boundary of  $R_w = 5$ . Note that the surface  $x = 0$  divides the workspace into two parts, and forces all the flow lines to approach the destination parallel to the y-axis.

To maintain network connectivity and navigate the robots to a common destination with a desired orientation using local information, the dipolar navigation function in [58]

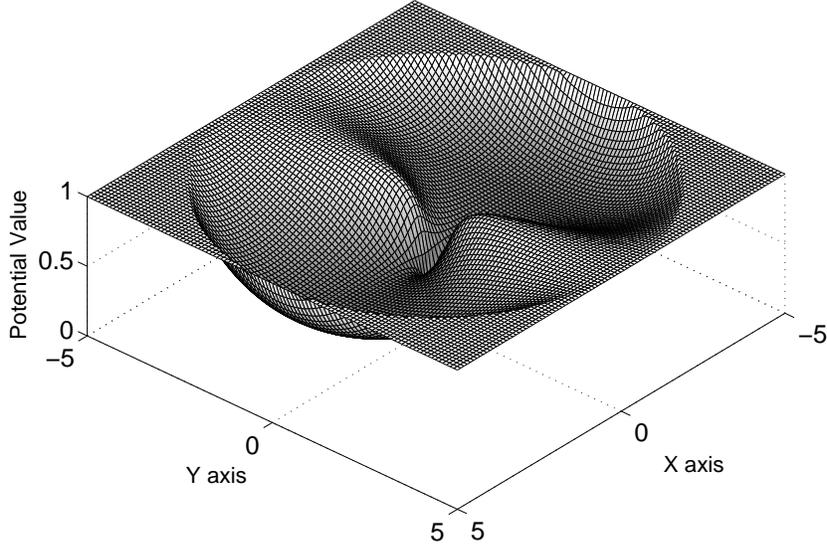


Figure 5-1. An example of a dipolar navigation function with workspace of  $R_w = 5$ , and the destination located at the origin with a desired orientation  $\theta^* = 0$ .

and [92] is modified for each node  $i$  as  $\varphi_i : \mathcal{F} \rightarrow [0, 1]$ ,

$$\varphi_i = \frac{\gamma_i}{(\gamma_i^\alpha + H_i \cdot \beta_i)^{1/\alpha}}, \quad (5-2)$$

where  $\alpha \in \mathbb{R}^+$  is a tuning parameter. The goal function  $\gamma_i(t) : \mathbb{R}^2 \rightarrow \mathbb{R}^+$  in (5-2) encodes the control objective of achieving the desired destination for node  $i$ , specified by the distance from  $p_i(t) \in \mathbb{R}^2$  to the common destination  $p^* \in \mathbb{R}^2$ , which is designed as

$$\gamma_i = \|p_i(t) - p^*\|^2. \quad (5-3)$$

The factor  $H_i(t) \in \mathbb{R}^+$  in (5-2) creates the repulsive potential of an artificial obstacle to align the trajectories at the destination with the desired orientation. The repulsive potential factor is designed as

$$H_i = \varepsilon_{nh} + \prod_{i=1}^N \eta_i, \quad (5-4)$$

where  $\varepsilon_{nh}$  is a small positive constant, and  $\eta_i(t) \in \mathbb{R}^+$  is designed as

$$\eta_i = \left( (p_i - p^*)^T \cdot n_{di} \right)^2, \quad (5-5)$$

where  $n_{di} \in \mathbb{R}^2$  is designed as

$$n_{di} = \begin{bmatrix} \cos(\theta_i^*) & \sin(\theta_i^*) \end{bmatrix}^T.$$

To ensure connectivity of the existing links between two nodes and restrict the motion of each node in the specified workspace, the constraint function  $\beta_i : \mathbb{R}^{2N} \rightarrow [0, 1]$  in (5-2) is designed as

$$\beta_i = B_{i0} \cdot \prod_{j \in \mathcal{N}_i} b_{ij}. \quad (5-6)$$

Specifically, the constraint function in (5-6) is designed to vanish whenever node  $i$  meets one of the constraints in the workspace, (i.e., if node  $i$  touches the workspace boundary, or departs from its neighbor nodes  $j \in \mathcal{N}_i$  to a distance of  $R$ ). A small disk area with radius  $\delta_1 < R$  centered at node  $i$  is denoted as a collision region. To prevent a potential collision between node  $i$  and the workspace boundary  $\partial\mathcal{F}$ , the function  $B_{i0} : \mathbb{R}^2 \rightarrow [0, 1]$  in (5-6) is designed as

$$B_{i0} = \begin{cases} -\frac{1}{\delta_1^2} d_{i0}^2 + \frac{2}{\delta_1} d_{i0}, & d_{i0} < \delta_1 \\ 1, & d_{i0} \geq \delta_1, \end{cases} \quad (5-7)$$

where  $d_{i0} \triangleq R_w - \|p_i\| \in \mathbb{R}$  is the relative distance of node  $i$  to the workspace boundary.

To ensure connectivity of the underlying graph, an escape region for each node is defined as the outer ring of the sensing and communication area with radius  $r$ ,  $R - \delta_2 < r < R$ , where  $\delta_2 \in \mathbb{R}^+$  is a predetermined buffer distance. Each edge formed by node  $i$  and the adjacent node  $j \in \mathcal{N}_i$  in the escape region have the potential to lose connectivity. In (5-6),  $b_{ij} \triangleq b(p_i, p_j) : \mathbb{R}^2 \rightarrow [0, 1]$  ensures connectivity of the network graph (i.e., guarantees that nodes  $j \in \mathcal{N}_i$  will never leave the sensing and communication zone of node  $i$  if node  $j$

is initially connected to node  $i$ ) and is designed as

$$b_{ij} = \begin{cases} 1 & d_{ij} \leq R - \delta_2 \\ -\frac{1}{\delta_2^2}(d_{ij} + 2\delta_2 - R)^2 \\ + \frac{2}{\delta_2}(d_{ij} + 2\delta_2 - R) & R - \delta_2 < d_{ij} < R \\ 0 & d_{ij} \geq R. \end{cases} \quad (5-8)$$

Since  $\gamma_i$  and  $\beta_i$  are guaranteed to not be zero simultaneously by Assumption 5.2, the navigation function candidate in (5-2) achieves its minimum of 0 when  $\gamma_i = 0$  and achieves its maximum of 1 when  $\beta_i = 0$ . Our previous work in [48] proves that the original navigation function modified to ensure connectivity, as designed in (5-8), is still a qualified navigation function. It is also shown in [36] that the navigation properties are not affected by the modification to a dipolar navigation with the design of (5-4), as long as the workspace is bounded,  $\eta_i$  in (5-5) can be bounded in the workspace, and  $\varepsilon_{nh}$  is a small positive constant. As a result, the decentralized navigation function  $\varphi_i$  proposed in (5-2) can be proven to be a qualified navigation function. See [48] and [36] for further details. From the properties of the navigation function, it is known that, if  $\varphi_i$  is a qualified navigation function, almost all initial positions (except for a set of measure zero points) asymptotically approach the desired destination.

### 5.2.2 Control Development

The desired orientation for robot  $i$ , denoted by  $\theta_{di}(t)$ , is defined as a function of the negative gradient of the decentralized navigation function in (5-2) as,

$$\theta_{di} \triangleq \arctan 2 \left( -\frac{\partial \varphi_i}{\partial y_i}, -\frac{\partial \varphi_i}{\partial x_i} \right), \quad (5-9)$$

where  $\arctan 2(\cdot) : \mathbb{R}^2 \rightarrow \mathbb{R}$  denotes the four quadrant inverse tangent function, and  $\theta_{di}(t)$  is confined to the region of  $(-\pi, \pi]$ . By defining

$$\theta_{di}|_{p^*} = \arctan 2(0, 0) = \theta_i|_{p^*},$$

$\theta_{di}$  remains continuous along any approaching direction to the goal position. Based on the definition of  $\theta_{di}$  in (5-9)

$$\nabla_i \varphi_i = - \|\nabla_i \varphi_i\| \begin{bmatrix} \cos(\theta_{di}) & \sin(\theta_{di}) \end{bmatrix}^T, \quad (5-10)$$

where  $\nabla_i \varphi_i = \begin{bmatrix} \frac{\partial \varphi_i}{\partial x_i} & \frac{\partial \varphi_i}{\partial y_i} \end{bmatrix}^T$  denotes the partial derivative of  $\varphi_i$  with respect to  $p_i$ , and  $\|\nabla_i \varphi_i\|$  denotes the Euclidean norm of  $\nabla_i \varphi_i$ . The difference between the current orientation and the desired orientation for robot  $i$  at each time instant is defined as

$$\tilde{\theta}_i(t) = \theta_i(t) - \theta_{di}(t), \quad (5-11)$$

where  $\theta_{di}(t)$  is generated from the decentralized navigation function in (5-2) and (5-9). Since  $\varphi_i$  in (5-2) is a qualified navigation function, the properties of a navigation function guarantees that  $q_{di}(t) \rightarrow q_i^*$  as  $t \rightarrow \infty$ . Hence, to achieve the navigation control objective,  $\theta_i(t)$  must track the desired orientation  $\theta_{di}(t)$ .

Based on the open-loop system in (5-1) and the subsequent stability analysis, the controller for each robot (i.e., the linear and angular velocity of robot  $i$ ) is designed as

$$v_i = k_v \|\nabla_i \varphi_i\| \cos \tilde{\theta}_i, \quad (5-12)$$

$$\omega_i = -k_w \tilde{\theta}_i + \dot{\theta}_{di}, \quad (5-13)$$

where  $k_v, k_w \in \mathbb{R}^+$ . The terms  $\nabla_i \varphi_i$  and  $\dot{\theta}_{di}$  in (5-12) and (5-13) are determined from (5-2) and (5-9) as

$$\nabla_i \varphi_i = \frac{\alpha (H_i \cdot \beta_i) \nabla_i \gamma_i - \gamma_i \nabla_i (H_i \cdot \beta_i)}{\alpha (\gamma_i^\alpha + H_i \cdot \beta_i)^{\frac{1}{\alpha} + 1}}, \quad (5-14)$$

where  $\nabla_i \gamma_i$  and  $\nabla_i (H_i \cdot \beta_i)$  are bounded in the workspace  $\mathcal{F}$  from (5-3) and (5-6), and

$$\dot{\theta}_{di} = k_v \cos(\tilde{\theta}_i) \begin{bmatrix} \sin(\theta_{di}) \\ -\cos(\theta_{di}) \end{bmatrix}^T \nabla_i^2 \varphi_i \begin{bmatrix} \cos(\theta_i) \\ \sin(\theta_i) \end{bmatrix}, \quad (5-15)$$

where  $\nabla_i^2 \varphi_i$  denotes the Hessian matrix of  $\varphi_i$  with respect to  $p_i$ . Substituting (5-12) into (5-1), the closed-loop system for robot  $i$  can be obtained as

$$\dot{p}_i = \begin{bmatrix} \dot{x}_i \\ \dot{y}_i \end{bmatrix} = k_v \|\nabla_i \varphi_i\| \cos \tilde{\theta}_i \begin{bmatrix} \cos \theta_i \\ \sin \theta_i \end{bmatrix}. \quad (5-16)$$

After using the fact that

$$\begin{bmatrix} \cos \theta_i & \sin \theta_i \end{bmatrix} \nabla_i \varphi_i = -\|\nabla_i \varphi_i\| \cos \tilde{\theta}_i, \quad (5-17)$$

from (5-10), the closed-loop error systems in (5-17) can be expressed as

$$\dot{p}_i = -k_v \nabla_i \varphi_i. \quad (5-18)$$

### 5.3 Connectivity and Convergence Analysis

#### 5.3.1 Connectivity Analysis

**Theorem 1:** Given an initially connected graph  $\mathcal{G}$  composed of nodes with kinematics given by (5-1), the controller in (5-12) and (5-13) ensure the graph remains connected.

*Proof.* Consider node  $i$  located at a point  $p_0 \in \mathcal{F}$  that causes  $\prod_{j \in \mathcal{N}_i} b_{ij} = 0$ , which will be true when either only one node  $j$  is about to disconnect from node  $i$  or when multiple nodes are about to disconnect with node  $i$  simultaneously. From (5-6),  $\beta_i = 0$ , which indicates that the navigation function designed in (5-2) achieves its maximum value. From the negative gradient of  $\varphi_i$  in (5-18), no open set of initial conditions can be attracted to the maxima of the navigation function [29]. Therefore, the existing edge between node  $i$  and node  $j \in \mathcal{N}_i$  will be maintained for all time.  $\square$

#### 5.3.2 Convergence Analysis

**Theorem 2:** Given an initially connected graph  $\mathcal{G}$  composed of nodes with kinematics given by (5-1), the controller in (5-12) and (5-13) ensure the robots converges to a common point with a desired orientation, in the sense that  $\|p_i(t) - p^*\| \rightarrow 0$  and

$\left| \tilde{\theta}_i(t) \right| \rightarrow 0$  as  $t \rightarrow \infty \forall i \in \mathcal{N}$ , provided that the tuning parameter  $\alpha$  in (5-2) is sufficient large,  $\alpha > \Theta$ .

*Proof.* Consider a Lyapunov function candidate

$$V(\mathbf{P}(t)) = \sum_{i=1}^N \varphi_i,$$

where  $\mathbf{P}(t)$  is the stacked position states of all nodes,  $\mathbf{P}(t) = \begin{bmatrix} p_1^T(t) & \cdots & p_N^T(t) \end{bmatrix}^T$ , and  $\varphi_i$  is the associated navigation function for node  $i$  designed in (5-2). The time derivative of  $V$  is

$$\begin{aligned} \dot{V} &= \sum_{i=1}^N (\nabla_i \varphi_1)^T \dot{p}_i + \cdots + \sum_{i=1}^N (\nabla_i \varphi_N)^T \dot{p}_i \\ &= \sum_{i=1}^N \sum_{j=1}^N \dot{p}_i^T (\nabla_i \varphi_j), \end{aligned}$$

which can be further separated as

$$\begin{aligned} \dot{V} &= \sum_{i: \nabla_i \varphi_i = 0} \left( \dot{p}_i^T (\nabla_i \varphi_i) + \sum_{j \neq i} \dot{p}_i^T (\nabla_i \varphi_j) \right) \\ &\quad + \sum_{i: \nabla_i \varphi_i \neq 0} \left( \dot{p}_i^T (\nabla_i \varphi_i) + \sum_{j \neq i} \dot{p}_i^T (\nabla_i \varphi_j) \right), \end{aligned} \quad (5-19)$$

where  $\nabla_i \varphi_j, \nabla_i \varphi_i \in \mathbb{R}^2$  denote the partial derivative of  $\varphi_j$  and  $\varphi_i$  with respect to  $p_i$ , respectively.

To show the objective of  $\|p_i - p^*\| \rightarrow 0 \forall i \in \mathcal{N}$ , the set of critical points,

$$S = \{p_i \mid \nabla_i \varphi_i = 0 \text{ for } \forall i \in \mathcal{N}\}$$

must be shown to be the largest invariant set of the stacked closed-loop system of (5-18).

When all nodes are located at the critical points (i.e., the position of node  $i$  satisfying  $\nabla_i \varphi_i = 0$ ) in (5-19),  $\dot{V} = 0$ , since  $\dot{p}_i = 0$  from (5-16). For node  $i$  not located at the critical points (i.e.,  $\nabla_i \varphi_i \neq 0$ ), (5-19) can be rewritten as

$$\dot{V} = \sum_{i: \nabla_i \varphi_i \neq 0} \left( \dot{p}_i^T (\nabla_i \varphi_i) + \sum_{j \neq i} \dot{p}_i^T (\nabla_i \varphi_j) \right). \quad (5-20)$$

To show that the set of critical points is the largest invariant set,  $\dot{V}$  must be strictly negative whenever there exists at least one node  $i$  such that  $\nabla_i \varphi_i \neq 0$ , for which it is sufficient to show that

$$\dot{p}_i^T (\nabla_i \varphi_i) + \sum_{j \neq i} \dot{p}_i^T (\nabla_i \varphi_j) < 0. \quad (5-21)$$

Substituting (5-14) and (5-18) into (5-21), yields

$$k_v (\nabla_i \varphi_i)^T (\nabla_i \varphi_i) + k_v \sum_{j \neq i} (\nabla_i \varphi_i)^T (\nabla_i \varphi_j) > 0,$$

which can be simplified as

$$\frac{1}{\alpha^2} c_1 + \frac{1}{\alpha} c_2 + c_3 > 0, \quad (5-22)$$

where

$$\begin{aligned} c_1 &= k_v \gamma_i \nabla_i^T (H_i \beta_i) \sum_{j \neq i} \gamma_j \nabla_i (H_j \beta_j), \\ c_2 &= -k_v H_i \beta_i \nabla_i^T \gamma_i \sum_{j \neq i} \gamma_j \nabla_i (H_j \beta_j), \\ c_3 &= k_v (\nabla_i \varphi_i)^T (\nabla_i \varphi_i), \end{aligned}$$

by using the fact that  $\nabla_i \gamma_j = 0$  from (5-3) and  $H_i, \beta_i, \gamma_i, \alpha$  are positive from (5-3), (5-4) and (5-6). A sufficient condition for the inequality in (5-22) to be satisfied is

$$-\frac{1}{\alpha^2} |c_1| - \frac{1}{\alpha} |c_2| > -c_3.$$

Hence, if  $\alpha > \Theta$ , where

$$\Theta = \max \left\{ \sqrt{\frac{|c_1|}{c_3}}, \frac{|c_2|}{c_3} \right\},$$

the system converges to the set of critical points. Applying LaSalle's invariance principle, the trajectories of the system converge to the largest invariant set contained in the set

$$S = \{\|\nabla_i \varphi_i\| = 0, \forall i \in \mathcal{V}\}. \quad (5-23)$$

The set in (5-20) is formed whenever the potential functions either reach the destination or a saddle point. Since  $\varphi_i$  in (5-2) is a navigation function, the saddle points of  $\varphi_i$  are

isolated in [60]. Thus, the set of initial conditions that lead to saddle points are sets of measure zero [98]. The largest invariant set constrained is the set of destination [99].

Hence,  $\|\nabla_i \varphi_i\| = 0$  indicates that  $\|p_i - p^*\| \rightarrow 0$  for  $\forall i$ .

To show that  $|\tilde{\theta}_i| \rightarrow 0$ , we take the time derivative of  $\tilde{\theta}_i(t)$  in (5-11) and use (5-1) to develop the open-loop orientation tracking error system as  $\dot{\tilde{\theta}}_i = \omega_i - \dot{\theta}_{di}$ . Using (5-13), the closed-loop orientation tracking error is

$$\dot{\tilde{\theta}}_i = -k_w \tilde{\theta}_i, \quad (5-24)$$

which has the exponentially decaying solution  $\tilde{\theta}_i(t) = \tilde{\theta}_i(0) e^{-k_w t}$ .

Based on (5-3) and (5-8), it is clear that  $\frac{\partial \varphi}{\partial x_i}, \frac{\partial \varphi}{\partial y_i} \in \mathcal{L}_\infty$  on  $\mathcal{F}$ ; hence, (5-12) can be used to conclude that  $v_i(t) \in \mathcal{L}_\infty$ . Provided  $\dot{\theta}_{di}(t) \in \mathcal{L}_\infty$  in (5-15) on  $\mathcal{F}$ , (5-13) can be used to show that  $\omega_i(t) \in \mathcal{L}_\infty$ . □

## 5.4 Simulation

A preliminary numerical simulation is performed in this section to demonstrate the performance of the controller developed in (5-12) and (5-13) in a scenario where a group of four mobile robots with the kinematics in (5-1) are navigated to the common destination  $[(p^*)^T, \theta^*]^T = [0 \ 0 \ 0]^T$ . The four mobile robots are deployed in a workspace of  $R_w = 5 \text{ m}$  with an initially connected condition of

$$\begin{bmatrix} q_1^T(0) \\ q_2^T(0) \\ q_3^T(0) \\ q_4^T(0) \end{bmatrix} = \begin{bmatrix} -2 & 1.5 & -1.131 \\ -2.25 & 0.7 & -1.7279 \\ -2.5 & -0.7 & 1.8850 \\ -2.25 & -1.5 & 0.9425 \end{bmatrix}.$$

The limited communication and sensing zone for each robot is assumed as  $R = 2 \text{ m}$  and  $\delta_1 = \delta_2 = 0.5 \text{ m}$ . The tuning parameter  $\alpha$  in (5-2) is selected as  $\alpha = 1.5$ , and the control gains  $k_v$  and  $k_w$  are adjusted to  $k_v = 1.1$  and  $k_w = 0.9$ . The control law in (5-12) and (5-13) yields the simulation results shown in Fig. 5-2 to Fig. 5-5. Fig. 5-2 shows

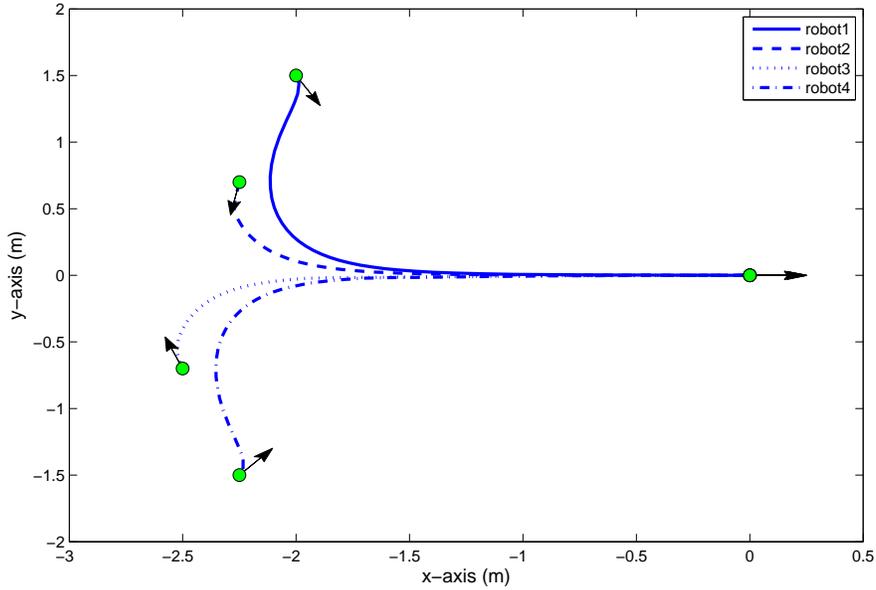


Figure 5-2. The trajectory for each mobile robot with the arrow denoting its current orientation.

the trajectory evolution for each robot, where the robots are represented by dots, and the associated arrows indicate the current orientation. The linear and angular velocity control inputs for each robot are shown in Fig. 5-3. In Fig. 5-4, the plot of position and orientation error for each mobile robot indicates that each robot achieves the common destination with the desired orientation. The evolution of inter-robot distance is shown in Fig. 5-5, which implies that the connectivity of the underlying graph is maintained, since the inter-robot distance is less than the radius  $R = 2 \text{ m}$  during the motion.

## 5.5 Summary

Based on the dipolar navigation function formalism, a decentralized time-varying continuous controller is developed to achieve network cooperative goals, that are navigating mobile robots to a common destination with a desired orientation and ensuring the network connectivity for all time, by using only local sensing information from one-hop neighbors. A distinguishing feature of the developed decentralized approach is that no inter-agent communication is required to complete the network rendezvous objective,

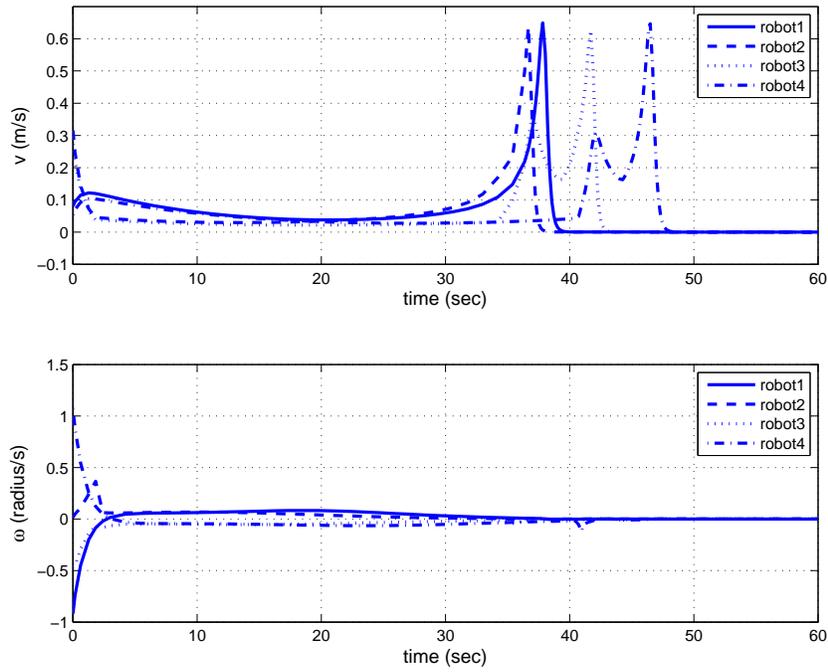


Figure 5-3. Plot of linear velocity and angular velocity for each mobile robot.

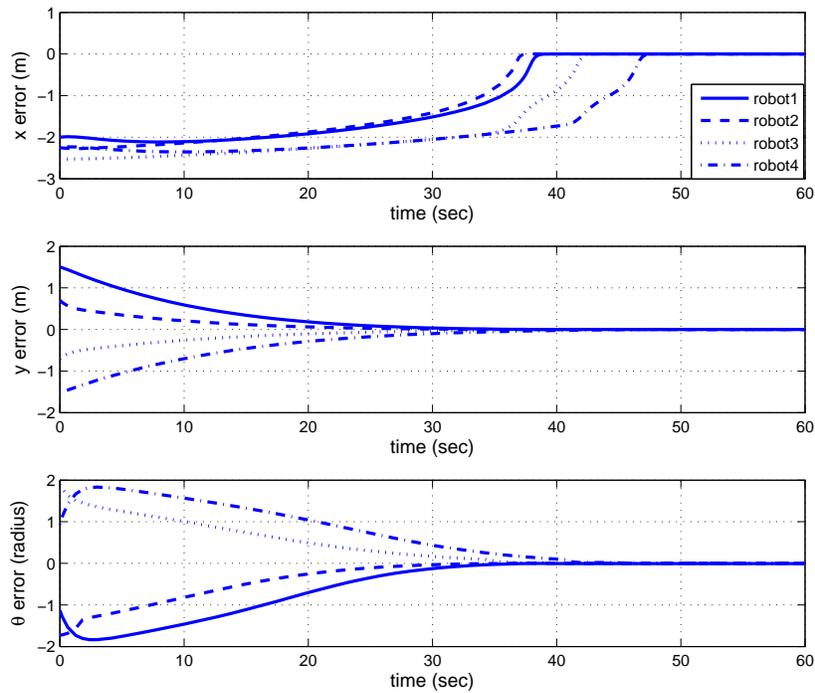


Figure 5-4. Plot of position and orientation error for each mobile robot.

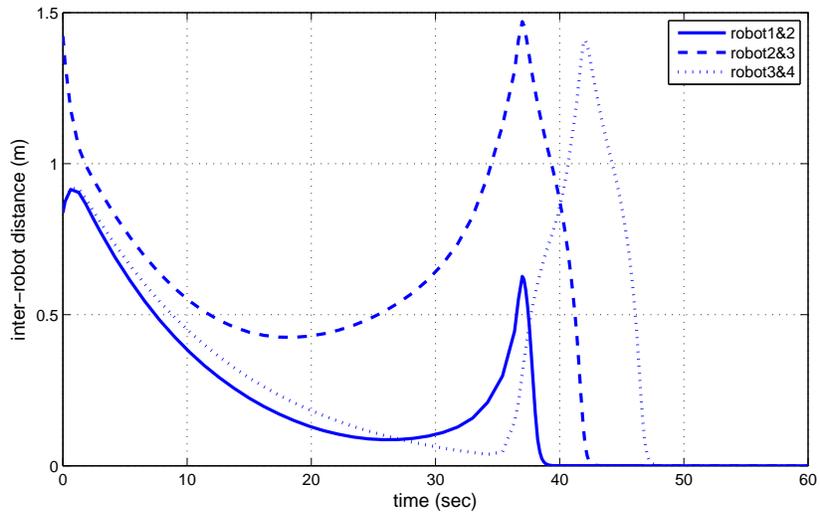


Figure 5-5. The evolution of inter-robot distance.

which results in radio silence during the network regulation. Future efforts are focused on enabling collision avoidance with obstacles in a dynamic environment using local sensing information.

## CHAPTER 6 INFLUENCING EMOTIONAL BEHAVIOR IN SOCIAL NETWORK

Chapter 2-5 focus on designing control algorithms for networked multi-agent systems in engineering, such as flocking, formation control and rendezvous problems. This chapter aims to study how can the models and methods developed in engineering be applied toward understanding and controlling a social network. How can one produce consensus among a social network (e.g., to manipulate social groups to a desired end)? Motivated towards this end, controllers developed in this chapter are to influence the emotions of a socially connected group of individuals to a consensus state. Using graph theory, a social network is modeled as an undirected graph, where an individual in the social network is represented as a vertex in the graph, and the social bond between two individuals is represented as an edge connecting two vertices. Due to the non-local property of fractional-order systems, the emotional response of individuals in the network are modeled by fractional-order dynamics whose states depend on influences from social bonds. Within this formulation, the social group is modeled as a networked fractional system. This chapter also considers a social bond threshold on the ability of two people to influence each other's emotions. To ensure interaction among individuals, one objective is to maintain existing social bonds among individuals above the prespecified threshold all the time (i.e., social controls or influences should not be so aggressive that they isolate or break bonds between people in the social group). Another objective is to design a distributed controller for each individual, using local emotional states from social neighbors, to achieve emotion synchronization in the social network (i.e., an agreement on the emotion states of all individuals). To achieve these objectives, a decentralized potential function is developed in [100] to encode the control objective of emotion synchronization, where maintenance of social bonds is modeled as a constraint embedded in the potential function. Asymptotic convergence of each emotion state to the

common equilibrium in the social network is then analyzed via a Metzler Matrix [42] and a Mittag-Leffler stability [82] approach.

## 6.1 Preliminaries

Fractional calculus and graph theory notions are introduced in this section, which serve as a basis for the subsequent development and analysis in this chapter.

### 6.1.1 Fractional Calculus

The uniform formula of a fractional integral with order  $\alpha \in (0, 1)$  is defined as

$${}_t D_t^{-\alpha} f(t) = \frac{1}{\Gamma(\alpha)} \int_{t_0}^t \frac{f(\tau)}{(t-\tau)^{1-\alpha}} d\tau, \quad (6-1)$$

where  ${}_t D_t^{-\alpha} f(t)$  denotes the fractional integral of order  $\alpha$  on  $[t_0, t]$ ,  $f(t)$  is an integrable function, and  $\Gamma(\cdot)$  denotes the Gamma function [77]. Caputo and Riemann-Liouville (R-L) fractional derivatives are the two most widely used fractional operators [77]. For an arbitrary real number  $p \in \mathbb{R}$ , the R-L and Caputo fractional derivatives are defined as

$${}_t D_t^p f(t) = \frac{d^{[p]+1}}{dt^{[p]+1}} ({}_t D_t^{-\alpha} f(t)),$$

and

$${}_t^C D_t^p f(t) = {}_t D_t^{-\alpha} \left( \frac{d^{[p]+1}}{dt^{[p]+1}} f(t) \right), \quad (6-2)$$

respectively, where  $\alpha = [p] + 1 - p \in (0, 1)$ ,  $[p]$  represents the integer part of  $p$ , and  ${}_t D_t^p$  and  ${}_t^C D_t^p$  are R-L and Caputo fractional derivatives with order  $p$  on  $[t_0, t]$ , respectively<sup>1</sup>.

Since the R-L fractional operator requires a fractional-order initial condition, which can be difficult to interpret [101], the subsequent development is based on the Caputo fractional operator.

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<sup>1</sup> If  $p$  is an integer, the Caputo derivative in (6-2) with  $\alpha = 1$  is equivalent to the integer order derivative.

Similar to the exponential function used in solutions of integer-order differential equations, the Mittag-Leffler (M-L) function given by

$$E_{\alpha,\beta}(z) = \sum_{k=0}^{\infty} \frac{z^k}{\Gamma(k\alpha + \beta)}, \quad (6-3)$$

where  $\alpha, \beta > 0$  and  $z \in \mathbb{C}$ , is frequently used in solutions of fractional-order systems.

Particularly, when  $\alpha = \beta = 1$ ,  $E_{\alpha,\beta}(z)$  in (6-3) is an exponential function,  $E_{1,1}(z) = e^z$ .

Consider the fractional order non-autonomous system

$${}^C D_t^\alpha x(t) = f(t, x) \quad (6-4)$$

with initial condition  $x(t_0)$ , where  $\alpha \in (0, 1)$ , and  $f(t, x)$  is piecewise continuous in  $t$  and locally Lipschitz in  $x$ . Stability of the solutions to (6-4) are defined by the M-L function as follows [82].

**Definition 6.1.** (Mittag-Leffler Stability) The solution of (6-4) is said to be Mittag-Leffler stable if

$$\|x(t)\| \leq \{m[x(t_0)] E_{\alpha,1}(-\lambda(t-t_0)^\alpha)\}^b,$$

where  $t_0$  is the initial time,  $\alpha \in (0, 1)$ ,  $b > 0$ ,  $\lambda > 0$ ,  $m(0) = 0$ ,  $m(x) \geq 0$ ,  $m(x)$  is locally Lipschitz, and  $E_{\alpha,1}$  is defined in (6-3) with  $\beta = 1$ .

Lyapunov's direct method is extended to fractional-order systems in the following Lemma to determine Mittag-Leffler stability for the solutions of (6-4) in [82].

**Lemma 6.1.** [82] *Let  $x = 0$  be an equilibrium point for the system (6-4), and  $\mathbb{D} \subset \mathbb{R}^n$  be a domain containing the origin. Let  $V(t, x) : (0, \infty] \times \mathbb{D} \rightarrow \mathbb{R}$  be a continuously differentiable function and locally Lipschitz with respect to  $x$  such that*

$$\begin{aligned} k_1 \|x\|^a &\leq V(t, x) \leq k_2 \|x\|^{ab}, \\ {}^C D_t^\beta V(t, x) &\leq -k_3 \|x\|^{ab}, \end{aligned}$$

where  $x \in \mathbb{D}$ ,  $\beta \in (0, 1)$ ,  $k_1, k_2, k_3, a$  and  $b$  are arbitrary positive constants. Then  $x = 0$  is Mittag-Leffler stable.

### 6.1.2 Graph Theory

Graph theory (see cf. [102]) is widely used to represent a networked system. Let  $\mathcal{G} = (\mathcal{V}, \mathcal{E})$  denote an undirected graph, where  $\mathcal{V} = \{v_1, \dots, v_N\}$  and  $\mathcal{E} \subset \mathcal{V} \times \mathcal{V}$  denote the set of nodes and the set of edges, respectively. Each edge  $(v_i, v_j) \in \mathcal{E}$  represents the neighborhood of node  $i$  and node  $j$ , which indicates that node  $i$  and node  $j$  are able to access each other's states. The neighbor set of node  $i$  is denoted as  $\mathcal{N}_i = \{v_j \mid (v_i, v_j) \in \mathcal{E}\}$ . A path between  $v_1$  and  $v_k$  is a sequence of distinct nodes starting with  $v_1$  and ending with  $v_k$  such that consecutive nodes are adjacent in graph  $\mathcal{G}$ . Graph  $\mathcal{G}$  is connected if in  $\mathcal{G}$  any node can be reached from any other node by following a series of edges. The adjacency matrix is defined as  $A \triangleq [a_{ij}] \in \mathbb{R}^{N \times N}$  with  $a_{ij} > 0$  if  $(v_i, v_j) \in \mathcal{E}$ , and  $a_{ij} = 0$  otherwise. A matrix  $L$  for the graph  $\mathcal{G}$  is defined as  $L \triangleq A - D \in \mathbb{R}^{N \times N}$ , where  $D \triangleq [d_{ij}] \in \mathbb{R}^{N \times N}$  is a diagonal matrix with  $d_{ii} = \sum_{j=1}^N a_{ij}$ . The  $N \times N$  matrix with positive or zero off-diagonal elements and zero row sums is referred as a Metzler matrix [103]. Zero is a trivial eigenvalue of a Metzler matrix, and all the other eigenvalues are positive, if and only if the corresponding undirected graph  $\mathcal{G}$  is connected. The eigenvector associated with the zero eigenvalue is  $\mathbf{1}$ , where  $\mathbf{1} = [1, \dots, 1]^T \in \mathbb{R}^N$ .

To facilitate the following development, a corollary to Theorem 1 of [42] is introduced as follows.

**Corollary 6.1.** *The equilibrium point  $x^* \mathbf{1} \in \mathbb{R}^N$  of the system*

$$\dot{x}(t) = L(t)x(t) \tag{6-5}$$

*is exponentially stable (i.e., the elements of  $x(t) \in \mathbb{R}^N$  achieve exponential consensus), provided that the time-varying matrix  $L(t) \in \mathbb{R}^{N \times N}$  in (6-5) is a Metzler matrix with piecewise continuous and bounded elements, and the time-varying graph corresponding to  $L(t)$  is connected for all  $t \geq 0$ .*

## 6.2 Problem Formulation

Consider a social network composed of  $N$  individuals. Using graph theory, the interaction among individuals is modeled as an undirected graph  $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ . For instance, the karate club network in [1] is modeled as an undirected graph as shown in Fig. 6-1, where the vertex in the graph  $\mathcal{G}$  is represented by an individual, the solid arrow connecting two individuals denotes the edge in  $\mathcal{G}$ , representing an established social bond (i.e., friendship) and indicating that the individuals are able to access each other's states (i.e., sense and understand the social state of a peer).

In a social network, the state of an individual can be the social status, social connections, emotional status, or etc. In the following development, the social state denotes some human emotion, such as happiness, love, anger or fear. The emotion state  $q_i(t) \in \mathbb{R}$  is a real number indicating the current state of an individual  $i$  that can be detected from other members (i.e., social neighbors such as close friends or family) in the social network. For instance, a greater value of  $q_i(t)$  implies a happier state of individual  $i$ .

An integer derivative of a function is only related to its nearby points, while a fractional-order derivative involves all the previous points. Since human emotions are always influenced by memories and past experiences,  $q_i(t)$  is modeled as the solution to a fractional-order dynamic as

$${}_0^C D_t^\alpha q_i(t) = u_i(t), \quad i = 1, \dots, N, \quad (6-6)$$

where  $u_i \in \mathbb{R}$  denotes an influence (i.e., control input) over the emotional state, and  ${}_0^C D_t^\alpha q_i(t)$  is the  $\alpha^{th}$  derivative of  $q_i(t)$  with  $\alpha \in (0, 1]$ . The model in (6-6) is a heuristic approximation to an emotional response. The model indicates that a person's emotional state is a direct relationship to external influence integrated over the history of a person's previous emotional states. On-going efforts by the scientific community are focused on the development of clinically derived models; yet, to date, there is no widely accepted model of a person's emotional response to events in a social network.

Social bonds in a network can be established through a number of relationships between individuals (e.g., student and teacher, employer and employee, patient and doctor, two strangers that share a common interest) and can be represented as an undirected edge in graph  $\mathcal{G}$ . Each bond has a weighting factor denoted as  $S_{ij} \geq 0$  that measures the amount of influence that is shared between individuals  $i$  and  $j$ . The greater the value  $S_{ij}$ , the closer the relationship between individuals  $i$  and  $j$ , and  $S_{ij} = 0$  if two individuals have no influence over each other. Through an analysis of a social graph over time, one could determine a weighting for the level of influence between individuals. However, the subsequent development only requires that an individual node has an understanding of the relative influence between itself and its local social neighbors. Moreover, it is assumed that, there exist a threshold  $\delta \in \mathbb{R}^+$ , and individuals  $i$  and  $j$  are able to influence each other's emotional states only when the social bond  $S_{ij} \geq \delta$ . In other words, an edge  $\varepsilon_{ij}$  in graph  $\mathcal{G}$  does not exist if the social bond  $S_{ij}$  between individuals  $i$  and  $j$  is less than the threshold  $\delta$ . The neighbors of individual  $i$  in graph  $\mathcal{G}$  is defined as  $\mathcal{N}_i = \{v_j \mid S_{ij} \geq \delta\}$ , which determines a set of individuals who have an influential relationship with individual  $i$ . In the subsequent development, the social bond is defined as

$$S_{ij} = f(\|q_i - q_j\|^2), \quad (6-7)$$

where  $f(\cdot)$  is a differentiable function, mapping the emotion states of individuals  $i$  and  $j$  to a real non-negative value. Some properties for  $S_{ij}$  include: 1)  $f(\|q_i - q_j\|^2)$  decreases as  $\|q_i - q_j\|$  increases (the further apart the emotional state of two individuals the less influence they have over each other), which indicates that  $\frac{\partial f}{\partial \|q_i - q_j\|} < 0$ ; 2)  $f(\|q_i - q_j\|^2)$  achieves the minimum of 0 when individual  $i$  has no influence/relationship with individual  $j$ ; 3) the second partial derivative  $\frac{\partial^2 f}{\partial q_i^2}$  is bounded. These properties are based on the general observation that the emotional states of individual  $i$  and  $j$  tend to consensus in a close relationship. For example, the emotional state of one spouse, parent or child tends to mirror the emotional state of another spouse, child, or parent respectively. Hence, it is

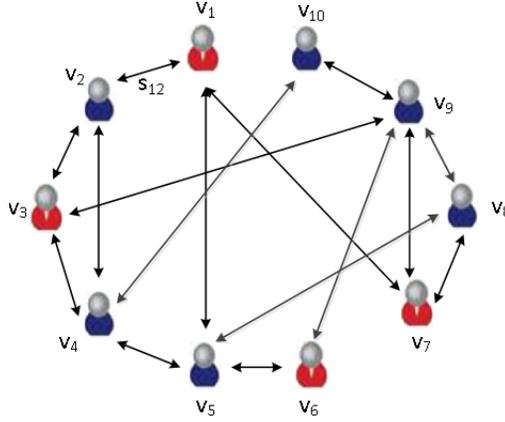


Figure 6-1. The Zachary's karate club network in [1] is modeled by an undirected graph  $\mathcal{G}$ , where the numbered vertex in the graph represents the members of the club, and solid line connecting two individuals denotes the established social bond (i.e., friendship) in the club.

reasonable to assume that  $S_{ij}$  is a function of the difference between  $q_i$  and  $q_j$ , designed as  $\|q_i - q_j\|^2$  in this work. While some discrete events can cause a discontinuous shift in someone's social bonds (e.g., a cheating spouse, winning the lottery, unexpected sickness or death) that would lead to an unbounded second partial derivative, most social bonds tend to be continuous over time.

Based on the problem setting, the social network of human emotions is now formulated as a networked fractional-order system described by (6-6). The emotion synchronization objective in a social network is to regulate the emotional states of individuals to a desired state (i.e.,  $q_i(t) \rightarrow q^*$  for all  $i$  with  $q^* \in \mathbb{R}$  denoting an equilibrium point). Moreover, individuals generally prefer to share an emotional response rather than react in an emotional way that renders them an outcast. Hence, the emotion synchronization problem also includes a goal that given an initially connected graph  $\mathcal{G}$ , the social bonds between individuals are maintained (i.e., maintain the social bonds  $S_{ij} \geq \delta$  all the time so that peers remain peers). Since social bonds exist initially, any two individuals are able to reach each other through a path of edges associated with a social bond satisfying  $S_{ij} \geq \delta$ .

### 6.3 Control Design

Artificial potential field based methods, composed of attractive and repulsive potentials, have been widely used in the control of multi-agent systems, where the control objective is encoded as the minimum potential value by the attractive potential and constraints are encoded as the maximum potential value by the repulsive potential (cf. [30, 104]). Driven by the negative gradient of the proposed potential field, the system will asymptotically achieve the minimum of the potential field. In this chapter, the potential field approach is applied to social control.

To achieve emotion synchronization, a decentralized potential function is developed as  $\varphi_i : \mathbb{R}^N \rightarrow [0, 1]$  for individual  $i$  (of  $N$ ) as

$$\varphi_i = \frac{\gamma_i}{(\gamma_i^k + \beta_i)^{1/k}}, \quad (6-8)$$

where  $k \in \mathbb{R}^+$  is a tuning parameter,  $\gamma_i : \mathbb{R}^2 \rightarrow \mathbb{R}^+$  is the goal function, and  $\beta_i : \mathbb{R}^N \rightarrow \mathbb{R}^+$  is a constraint function. The goal function in (6-8) is designed as

$$\gamma_i = \sum_{j \in \mathcal{N}_i} \frac{1}{2} \|q_i - q_j\|^2, \quad (6-9)$$

which is minimized whenever the emotional state of individual  $i$  agrees with the emotions of neighbors  $j$ ,  $j \in \mathcal{N}_i$ . To ensure existing social bonds are maintained (i.e.,  $S_{ij} \geq \delta$ ), the constraint function in (6-8) is designed as

$$\beta_i = \prod_{j \in \mathcal{N}_i} \frac{1}{2} b_{ij}, \quad (6-10)$$

where  $b_{ij} = S_{ij} - \delta$ , and  $S_{ij}$  is defined in (6-7). For an existing social bond between individuals  $i$  and  $j$ , the potential function  $\varphi_i$  in (6-8) will approach its maximum whenever the constraint function  $\beta_i$  decreases to 0 (i.e., the social bond  $S_{ij}$  decreases to the threshold of  $\delta$ ).

Based on the definition of the potential function in (6–8), the emotional influence is designed as

$$u_i = -K_i \nabla_{q_i} \varphi_i, \quad (6-11)$$

where  $K_i$  is a positive gain. In (6–11),  $\nabla_{q_i} \varphi_i$  denotes the gradient of  $\varphi_i$  with respect to  $q_i$ , as

$$\nabla_{q_i} \varphi_i = \frac{k\beta_i \nabla_{q_i} \gamma_i - \gamma_i \nabla_{q_i} \beta_i}{k(\gamma_i^k + \beta_i)^{\frac{1}{k}+1}}. \quad (6-12)$$

From (6–9) and (6–10),  $\nabla_{q_i} \gamma_i$  and  $\nabla_{q_i} \beta_i$  in (6–12) can be determined as

$$\nabla_{q_i} \gamma_i = \sum_{j \in \mathcal{N}_i} (q_i - q_j), \quad (6-13)$$

and

$$\begin{aligned} \nabla_{q_i} \beta_i &= \sum_{j \in \mathcal{N}_i} \bar{b}_{ij} \frac{1}{2} \nabla_{q_i} b_{ij} \\ &= \sum_{j \in \mathcal{N}_i} \left( \frac{\partial f}{\partial (\|q_i - q_j\|^2)} \right) \bar{b}_{ij} (q_i - q_j), \end{aligned} \quad (6-14)$$

respectively, where  $\bar{b}_{ij} \triangleq \prod_{l \in \mathcal{N}_i, l \neq j} b_{il}$ . Substituting (6–13) and (6–14) into (6–10),  $\nabla_{q_i} \varphi_i$  is rewritten as

$$\nabla_{q_i} \varphi_i = - \sum_{j \in \mathcal{N}_i} m_{ij} (q_i - q_j), \quad (6-15)$$

where

$$m_{ij} = \frac{k\beta_i - \bar{b}_{ij} \gamma_i \left( \frac{\partial f}{\partial (\|q_i - q_j\|^2)} \right)}{k(\gamma_i^k + \beta_i)^{\frac{1}{k}+1}} \quad (6-16)$$

is non-negative, based on the first property of  $S_{ij}$ , and the definition of  $\gamma_i$ ,  $\beta_i$ ,  $k$ , and  $\bar{b}_{ij}$ .

#### 6.4 Convergence Analysis and Social Bond Maintenance

To show that individuals in the fractional-order network converge to a common desired emotional state, the following analysis is segregated into three proofs. In the first proof, the connectivity of the social group is proven to be ensured by the influence function in (6–11). In the second proof, an integer-order simplification of the dynamic system in (6–6) is considered and exponential convergence is proven. Exponential convergence of

the integer-order system is used to establish the existence of a Lyapunov function and its derivative by invoking a converse Lyapunov theorem. The Caputo fractional derivative of the developed Lyapunov function is then determined and used within a Mittag-Leffler stability analysis that proves the closed-loop fractional-order system asymptotically converges to the equilibrium set of consensus states.

#### 6.4.1 Social Bond Maintenance

Assuming a social network is initially connected, the social group will remain connected if every existing edge in the network graph is maintained all the time (i.e.,  $S_{ij} \geq \delta$ ). The following Lemma is developed to show that connectivity of the underlying graph is maintained under the influence function in (6-11) (i.e., social peers do not become isolated and disconnected from the social group).

**Lemma 6.2.** *The influence function in (6-11) guarantees connectivity of  $\mathcal{G}$  all the time.*

*Proof.* Consider an emotional state  $q_0$  for individual  $i$ , where the bond between individual  $i$  and neighbor  $j \in \mathcal{N}_i$  satisfies  $b_{ij}(q_0, q_j) = 0$ , which indicates that the social bond is too weak to affect the emotion of individual  $i$ , and the associated edge is about to break. From (6-10),  $\beta_i = 0$  when  $b_{ij} = 0$ , and the navigation function  $\varphi_i$  achieves its maximum value from (6-8). Since  $\varphi_i$  is maximized at  $q_0$ , no open set of initial conditions can be attracted to  $q_0$  under the negated gradient control law designed in (6-11). Therefore, the social bond between individual  $i$  and  $j$  is maintained greater than  $\delta$  by (6-11), and the associated edge is also maintained. Following similar arguments, every edge in  $\mathcal{G}$  is maintained, and connectivity of the underlying graph is guaranteed. □

#### 6.4.2 Convergence Analysis

For the particular case of  $\alpha = 1$ , the fractional-order dynamics in (6-6) simplifies to the integer-order system  $\dot{q}_i(t) = u_i(t)$ . The following theorem establishes exponential convergence to the common equilibrium for the integer-order system.

**Theorem 6.1.** *The equilibrium point  $q^* \in \mathbb{R}$  of the initially connected graph of nodes with integer-order dynamics  $\dot{q}_i(t) = u_i(t)$  is exponentially stable for all  $i$ , given the influence function  $u_i(t)$  developed in (6-11).*

*Proof.* For  $\alpha = 1$ , substituting (6-11) and (6-15) into (6-6) yields the following closed-loop emotion dynamics of individual  $i$ :

$$\dot{q}_i(t) = - \sum_{j \in \mathcal{N}_i} K_i m_{ij} (q_i - q_j). \quad (6-17)$$

Using (6-17) and similar to [9], the dynamics of all individuals in the social network can be rewritten in a compact form as

$$\dot{\mathbf{q}}(t) = \pi(t) \mathbf{q}(t), \quad (6-18)$$

where  $\mathbf{q} = \begin{bmatrix} q_1, & \dots, & q_N \end{bmatrix}^T$  denotes the stacked vector of  $q_i$ , and the elements of  $\pi(t) \in \mathbb{R}^{N \times N}$  are defined as

$$\pi_{ik}(t) = \begin{cases} - \sum_{j \in \mathcal{N}_i} K_i m_{ij} & i = k \\ K_i m_{ij} & j \in \mathcal{N}_i, i \neq k \\ 0, & j \notin \mathcal{N}_i, i \neq k. \end{cases} \quad (6-19)$$

From (6-19),  $\pi(t)$  is matrix with zero row sums. Using the fact that  $m_{ij}$  is non-negative from (6-16), and  $K_i$  is a positive constant gain in (6-11), the off-diagonal elements of  $\pi(t)$  are positive or zero, and its row sums are zero. Hence,  $\pi(t)$  is a Metzler matrix.

Given that  $\pi(t)$  is a Metzler matrix and the social network is always connected with the controller developed in (6-11) (see Lemma 6.2), Corollary 6.1 can be applied to (6-18) to conclude that the elements of  $\mathbf{q}(t)$  exponentially achieve consensus.  $\square$

**Theorem 6.2.** *The equilibrium point  $q^* \in \mathbb{R}$  of the initially connected graph of nodes with the fractional-order dynamics in (6-6) with  $\alpha \in (0, 1)$  is asymptotically stable for all  $i$ , given the influence function  $u_i(t)$  developed in (6-11).*

*Proof.* Let  $x_i(t) \triangleq q_i(t) - q^* \in \mathbb{R}$  and  $\mathbf{x}(t) \triangleq \mathbf{q}(t) - q^*\mathbf{1} \in \mathbb{R}^n$ . The fractional-order dynamics in (6–6) with  $\alpha \in (0, 1)$  for all individuals can be obtained from (6–18) as

$${}_0^C D_t^\alpha \mathbf{x}(t) = \pi(t) (\mathbf{x}(t) + q^*\mathbf{1}) \triangleq g(t, \mathbf{x}), \quad (6-20)$$

where  $\pi(t)$  is the same as in Theorem 6.1, since each element in  $\pi(t)$  is a function of  $q_i(t) - q_j(t)$  from (6–16) and  $q_i(t) - q_j(t) = x_i(t) - x_j(t)$ . Since the stability of a fractional-order system is defined by Definition 6.1, and Mittag-Leffler stability implies asymptotic stability as discussed in [82], the following development is focused on proving that (6–20) is Mittag-Leffler stable.  $\square$

Since  $\gamma_i$  and  $\beta_i$  are not zero simultaneously, and  $\gamma_i, \beta_i$  and their partial derivatives are bounded from (6–13) and (6–14),  $\pi(t)$  in (6–20) is bounded. Assuming that  $\pi(t)$  is bounded by a constant  $l \in \mathbb{R}^+$ , the Lipschitz condition for  $g(t, \mathbf{x})$  in (6–20) is

$$\frac{\|g(t, \mathbf{x})\|}{\|\mathbf{x}\|} \leq l. \quad (6-21)$$

Theorem 6.1 states that the equilibrium point  $q^*$  is exponentially stable for the integer-order system of (6–18). The converse Lyapunov theorem, Theorem 4.9 in [105], indicates that there exists a function<sup>2</sup>  $V(t, \mathbf{x}) : (0, \infty] \times \mathbb{R}^N \rightarrow \mathbb{R}$  and strictly positive constants  $k_1, k_2$ , and  $k_3$  such that

$$k_1 \|\mathbf{x}\| \leq V(t, \mathbf{x}) \leq k_2 \|\mathbf{x}\|, \quad (6-22)$$

$$\dot{V} \leq -k_3 \|\mathbf{x}\|. \quad (6-23)$$

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<sup>2</sup> As discussed in [42], one valid selection for the Lyapunov function is  $V(x) = \max \{ x_1, \dots, x_n \} - \min \{ x_1, \dots, x_n \}$ .

Let  $\beta = 1 - \alpha \in (0, 1)$ . Following a similar procedure in the proof of Theorem 8 in [82] and using (6-21) and (6-23), the Caputo fractional derivative of  $V$  is computed as

$$\begin{aligned}
{}_0^C D_t^\beta V(t, \mathbf{x}) &= {}_0^C D_t^{1-\alpha} V(t, \mathbf{x}) = {}_0^C D_t^{-\alpha} \dot{V} \\
&\leq -k_3 ({}_0^C D_t^{-\alpha} \|\mathbf{x}\|) \\
&\leq -k_3 \left( {}_0^C D_t^{-\alpha} \frac{\|g(t, \mathbf{x})\|}{l} \right) \\
&\leq -\frac{k_3}{l} \|{}_0^C D_t^{-\alpha} g(t, \mathbf{x})\| \\
&\leq -\frac{k_3}{l} \|\mathbf{x}\|. \tag{6-24}
\end{aligned}$$

Mittag-Leffler stability of system (6-20) with  $\alpha \in (0, 1)$  can be obtained as

$$x(t) \leq \frac{V(0, x(0))}{k_1} E_{1-\alpha} \left( -\frac{k_3}{k_2 l} t^{1-\alpha} \right), \tag{6-25}$$

by applying Lemma 6.1 to (6-22) and (6-24), where  $a = b = 1$ . The result in (6-25) implies the equilibrium point  $q^* \mathbf{1} \in \mathbb{R}^n$  of the closed-loop fractional-order system in (6-20) is asymptotically stable.

## 6.5 Discussion

The previous development is based on the assumption that  $q^*$  is a common equilibrium point for all the individuals in a social network. In some situations, a common equilibrium point for an emotional state (e.g., group anger) could be derived from a discrete event (e.g., a police shooting [66, 67]) or long term events (e.g., years of oppression from a dictator [68, 69]). In such situations, the controller in (6-11) provides instructions for an individual to combine emotional differences with social peers, while considering the strength of the respective social bonds, so that as the individual's emotional state converges to  $q^*$ , social bonds (i.e., the need for peers to share an emotional state) between peers will also influence them to converge to the same emotional state. If a person instantly converges to  $q^*$ , the emotional difference between social peers may decrease to the point where  $S_{ij} < \delta$ , resulting in a separation from the social group and an end of the

individual's influence over the group (i.e., the change in emotional state is great enough that bonds between social peers are broken and the social peers ignore the individual's state). The controller in (6–11) accounts for the weighted interactions and influence over peers based on the assumption that peers will integrate an emotional state in a non-local fractional-order sense.

Of course, individuals in a social network often do not have a common equilibrium point. For example, a group of friends may wish to engage in an activity that differs from the desire of an individual. In these scenarios, a person must resolve the conflict between the individual equilibrium point and the social bond constraint that  $S_{ij} \geq \delta$ . That is, either peer pressure will deviate the person from the desired social state, strengthening corresponding social bonds, or social bonds with the group will decrease/break. This observation indicates that long term peers with strong social bonds likely share a common equilibrium point. Follow-on efforts to the current chapter are being developed to incorporate the dynamics of the equilibrium point/social bond arbitration along with influence strategies to enable social peers to deviate a person from an equilibrium, or change the equilibrium.

## 6.6 Summary

In this chapter, emotion synchronization for a group of individuals in a social network is studied. By modeling human emotion as a fractional-order system, a decentralized potential field-based function is developed to ensure that the emotion states of all individuals asymptotically converge to a common equilibrium while maintaining social bonds. Social bonds play an import role in a person's emotional state. For instance, a person tends to put greater trust in a close friend than some random person, and thus, can be more easily influenced by the close friend. However, the current development only examines the social bond as a threshold constraint to ensure continued interaction between friends, without considering the potential dynamics of how a person's emotions can be affected by different social bonds in the network. Hence, future work is being considered that explores the

relation between a person's emotion and the associated different levels of social bonds. Moreover, further efforts are also targeting influence strategies to enable social peers to deviate a person from an equilibrium, or change the equilibrium (i.e., peer pressure strategies applied to reluctant peers).

## CHAPTER 7 CONCLUSION AND FUTURE WORK

This chapter concludes the dissertation by discussing the main contributions developed in each chapter and the open problems for future research.

### 7.1 Conclusion

Various applications can benefit from coordination and collaboration among a group of agents, such as sensing, searching and rescue. To efficiently exchange information and make appropriate decisions for a multi-agent system, agents are typically required to collaborate over a wireless communication network. The focus of this dissertation is to develop a control strategy for a group of agents with limited communication and sensing capabilities to achieve collective tasks. Since each agent knows the positions of only those agents within its sensing range and can only communicate with nodes within its communication range, the tasks must be accomplished while ensuring that specified nodes stay within each other's sensing and communication ranges and that the overall communication network stays connected. Artificial potential field based controllers are developed to preserve overall network connectivity and enable cooperative tasks such as formation control and the rendezvous problems in Chapter 2 - Chapter 5. The results in Chapter 2 - Chapter 5 mainly focus on control designs for multi-agent systems to perform cooperative control objectives in engineering. In Chapter 6, the models and methods are extended toward understanding and exerting influence within a social network. The specific contributions of each chapter are summarized as follows.

In Chapter 2, a two stage control framework is developed to achieve the cooperative control objective of maintaining global network connectivity during the mission by grouping all nodes into two subgraphs, a high level network subgraph and several low level network subgraphs. The key to maintain network connectivity is to ensure connectivity within the high level subgraph and each low level subgraph. A potential-field-based controller is then designed to ensure that the high level subgraph and each low level

subgraph are always connected if they are connected initially, and achieve collision avoidance among agents when performing desired tasks.

In Chapter 3, given an initial graph with a desired neighborhood, a navigation function based decentralized controller is developed to ensure the system asymptotically converges to the desired configuration while maintaining network connectivity and avoiding collisions with other agents and obstacles. Contrary to other potential field based approaches which can be trapped by local minima, using the navigation function framework in this chapter, the system is guaranteed to achieve its global minimum, which corresponds to the desired configuration. Another feature of the developed approach is that the desired global configuration can be achieved by a group of agents using only local sensing feedback without requiring radio communication among agents, which enables a stealth mode of operation.

In Chapter 4, the assumption of an initial graph with a desired neighborhood in Chapter 3 is eliminated. A novel strategy, using a prefix labeling and routing algorithm from [52] and a navigation function based control scheme from [94], is developed to achieve a desired formation for a group of identical agents from an arbitrarily connected initial graph. Since the agents considered in this chapter are identical, the agents can take any position in the final topology. Contrary to an assumption in most existing work in formation control (cf. [2, 26, 27] and their references) where the absolute or relative poses of the agents are prespecified, and the initial topology is required to be a supergraph of the desired topology, the approach developed in Chapter 4 enables formation control from an arbitrary initial condition, only assuming that the final topology of the desired physical configuration is a tree. Based on the navigation function framework, the desired formation is guaranteed to be achieved with collision avoidance among agents during the motion, and network connectivity is ensured by modeling the underlying graph connectivity as an artificial constraint in the navigation function. Moreover, the concept of information flow is applied to find a path with more freedom for the motion of extra nodes without

partitioning network and allows some communication links to be formed or broken in a smooth manner without introducing a discontinuity.

In Chapter 5, a decentralized continuous time-varying controller, using only local sensing feedback from its one-hop neighbors, is developed to reposition and reorient a group of wheeled robots with nonholonomic constraints to a common setpoint with a desired orientation while maintaining network connectivity during the evolution. Using the navigation function framework, the multi-agent system is guaranteed to maintain connectivity and be stabilized at a common destination with a desired orientation without being trapped by local minima. Moreover, the result can be extended to other applications by replacing the objective function in the navigation function to accommodate for different tasks, such as formation control, flocking, and other applications.

In Chapter 6, a distributed controller for each individual in a social network is designed, using local emotional states from social neighbors, to achieve emotion synchronization for a group of individuals in a social network (i.e., an agreement on the emotion states of all individuals). Motivated by the non-local property of fractional-order systems, the emotional response of individuals in the network are modeled by fractional-order dynamics whose states depend on influences from social bonds. Using graph theory, a social network is modeled as an undirected graph, where an individual in the social network is represented as a vertex in the graph, and the social bond between two individuals is represented as an edge connecting two vertices. Encoding the control objective of emotion synchronization and modeling the maintenance of social bonds as a constraint, a potential function is developed to ensure asymptotic convergence of each emotion state to the common equilibrium in the social network.

## 7.2 Future work

The work in Chapter 2 to Chapter 5 illustrates that potential field based control methods can be successfully applied for multi-agent systems to perform cooperative control tasks while maintaining network connectivity during the mission. The work in

Chapter 6 then applies the control techniques developed in engineering to investigate and influence emotions of people in a social network, which opens new avenues for future research in the domain of social engineering. Since the study for a social network is a promising area and research in this area is still at a nascent stage, several interesting open problems still exist. In this section, open problems related to multi-agent systems in engineering and the control design in social networks in this dissertation are discussed .

Future work for multi-agent system in engineering:

1. In Chapter 3, it is assumed that no other obstacles or agents can be within the collision region of node  $i$  when node  $i$  is about to break the communication link. In addition, the probability of more than one simultaneous collision with node  $i$  is assumed negligible, which may become less practical as a point grows to a sphere in the presence of uncertainty, and as the workspace becomes more crowded.
2. In Chapter 4, the topology of the final formation is required to be a tree. If this assumption can be eliminated, the formation control problem can be formulated as the desire to achieve any desired formation from any arbitrary initial graph.
3. In Chapter 5, one objective is for a group of agents with nonholonomic constraints to meet at the same destination. An interesting extension is to consider agents with more complicated constraints and dynamics, such as unmanned air or underwater vehicle.

Future work in control development for a social network:

1. The dynamic model given in Chapter 6 is a heuristic approximation to an emotional response. The model indicates that a person's emotional state is a direct relationship to external influence integrated over the history of a person's previous emotional states. On-going efforts by the scientific community are focused on the development of clinically derived models. Future work is required to include more precise clinical emotional models to describe a person's emotional response to events in a social network, instead of using the heuristic approximation in Chapter 6.

2. In Chapter 6, a social network is modeled as a undirected graph, where an individual in the social network is represented as a vertex in the graph, and the social interaction between two individuals is represented as an undirected edge of a certain weight connecting two vertices. If two nodes are connected, they may influence each other through their social interaction (i.e., the undirected edge). However, the influence between two nodes may or may not be symmetric. In other words, the graph can be undirected, directed, or mixed. The magnitude and direction (or lack of) describing the edges between nodes may be defined through the use of an influence function. For instance, people usually interact with different numbers of individuals and with some individuals more than others. Hence, people can be more influenced by peers with different social bonds. Modeling a social network as an undirected, directed or even mixed graph, and studying the interaction among nodes within each type of graph should be pursued as future work.
3. Social bond are defined in Chapter 6 as a weighted edge measuring the amount of influence that is shared between individuals. It is assumed that, there exist a threshold  $\delta \in \mathbb{R}^+$ , and two individuals are able to influence each other's emotional states only when their social bond is greater than  $\delta$ . An interesting problem is how individuals influence each other. Do the social bonds need to be above an influence threshold? Does there have to be a direct connection?
4. Chapter 6 assumes that  $q^*$  is a common equilibrium point for all the individuals in a social network. However, individuals in a social network can have different equilibrium points. For example, a group of friends may wish to engage in an activity that differs from the desire of an individual. Follow-on efforts to the current work are being developed to incorporate the dynamics of the equilibrium point/social bond arbitration along with influence strategies to enable social peers to deviate a person from an equilibrium, or for a person to change the equilibrium of the group.

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