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Ph.D. Thesis Outline

Resilient Consensus of Multi-Agent Networks in the Presence of Malicious Attacks

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Background: In recent years, cyber security has emerged as an important and critical issue in the area of control systems. Due to the wide spread use of shared networks in control systems, it is now well recognized that many vulnerabilities for potential cyber-attacks are present.

In this research, we approached the issue of security in the context of Multi-Agent Systems (MASs), which are networks of agents cooperating with each other to obtain a global achievement in the entire network. Each agent has access to only its neighboring agents, and hence efficient usage of local information is critical to coordinate a potentially large number of agents with low capability for computation and communication. Such systems have many applications including formations of unmanned autonomous vehicles (UAVs), power networks, opinion dynamics, and clock synchronization. Extensive studies on multi-agent control problems have been carried out in the past decade.

Our Achievements: We have focused on resilient consensus problems where the aim is to reach agreement on specific variables that the agents have, but certain agents in the network anonymously try to mislead others. Such malicious agents do not follow the predefined local interaction rules and have global information regarding the network. This type of problems has been long studied in the area of distributed algorithms in computer science since 1980s. However, our approach is based on the viewpoint of multi-agent control, which has provided new motivations and more realistic problem settings for UAV type applications. In particular, we have incorporated the dynamics of the agents and have also found conditions on the network structure of agents' interactions. To enhance the security level, we have introduced a simple rule where each normal agent ignores some of its neighbors which take the most deviated values. Such algorithms are known as Mean Sequence Reduced (MSR) algorithms in computer science and more recently in control. For different versions of resilient consensus problems, we have obtained sufficient conditions and necessary conditions especially on network structures. These conditions are stated in terms of the so-called graph robustness, which is a

connectivity measure of graphs. As expected, the graph must have more connectivity and more interactions among agents to handle a larger number of malicious agents. We can highlight the contributions of this research in three aspects:

1. Agent models: Motivated by applying resilient control to autonomous vehicles and robots, we have considered agent models with second-order dynamics, which are more suitable for such applications. In the network, each normal agent uses both position and velocity values to update its own movement. We also proposed these algorithms for integer-valued (quantized) agent networks.

2. Network structures: We have fully characterized the resiliency of MSR algorithms based on the notion of graph robustness. This is aligned with the current research on multi-agent control systems where the minimum conditions on network structures have been studied. By contrast, in computer science, agents are often assumed to be computers, which means that network structures can be considered to be of all-to-all type (i.e., complete graphs).

3. Asynchronous updates with delayed information: Our study has been extended from synchronous update schemes with no delay in the neighbors' information to asynchronous updates schemes with bounded delays. The communication model here is suitable for real-time control of vehicles.

Outline: The thesis is organized as follows. In Chapter 2, we provide the basic concepts in multi-agent networks and security related to the thesis. The notion of robust graphs and MSR algorithms are summarized and an overview of the related works is presented. In Chapter 3, we extend the previous results in the literature to a more realistic model which has both asynchrony and delays. Our viewpoint has been motivated by the recent literature in control on multi-agent systems and has led us to introduce features in the update schemes and communication delays different from those in computer science. Chapter 4 proposes an extended version of the MSR-type algorithms to tackle the problem of resilient consensus in second-order networks. We derive the solutions for two classes of malicious networks. As we will see the conditions are consistent with those obtained in the literature. Chapter 5 is devoted to the asynchronous counterpart of Chapter 4 where the agents make use of old information at their idle times. We find here that the same conditions as those in Chapter 3 must hold. Chapter 6 proposes a novel probabilistic model for quantized agent networks and analyzes its resiliency through an

MSR-type algorithm. As a side result, the convergence of the proposed algorithm without any malicious agents is considered. We will see also that randomization in update times make a relaxation in the sufficient condition of asynchronous updates. Finally, Chapter 7 summarizes the results and open problems and new interesting directions for the future research are discussed.