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Book Review: Distributed Consensus in Multi-Vehicle Cooperative Control –Theory and Application–

by Wei Ren and Randal W. Beard

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I. Objectives and Motivations

The book closely examines the problem of information consensus for cooperative control of multiple vehicle system. The objective of this book is to give summary about the work done by the author in cooperative control using distributed consensus algorithms. As claimed in the preface section, the book addresses the problem of information consensus, where a team of vehicles must communicate with each other to coordinate their tasks. The challenging nature of this subject is derived from limitations that occur in any known means of communication. Information flow and sharing problems also enrich the challenge.

II. Contents

The book consists of 14 chapters and 6 appendices. The first 7 chapters present the theoretical results on distributed consensus algorithms, and the remaining chapters present various experimented applications in cooperative control which involve ground and aerial robots. The 6 appendices present various subjects and techniques prerequisite to the book's subject.

Chapter 1 presents an overview of consensus algorithms in cooperative control, which includes literature review on consensus algorithms, with fundamental concept, convergence analysis and synthesis of consensus algorithms, and coordination strategy design. At the beginning of the chapter, it discusses background of cooperative system development, comparison with the single autonomous system, and potential applications. It also discusses the challenges in both theoretical and practical aspects.

Chapter 2 presents discussion about consensus algorithms for single-integrator dynamics, or 1st order dynamics. Subject of discussion involves both fixed and dynamic interaction topologies, for both continuous-time and discrete-time systems each. The discussion begins on fundamental algorithms with two preliminary results, for continuous-time and discrete-time algorithms respectively. Necessary and sufficient conditions for each case of consensus of information are derived afterwards. Results of information consensus simulation for system under changing interaction topologies using discrete-time and continuous-time algorithms are presented.

Advancing further on consensus algorithms for 1st order dynamics, Chapter 3 discusses consensus tracking with a reference state, constant and time-varying reference state, of 1st order system. Starting with problem statement in the first section, both cases are discussed separately in two different sections. As for consensus tracking with time-varying reference state, the discussion includes cases where information about reference state is only available for some individual systems, cases where control effort in the system is bounded, and cases where information from individual systems are feedback to the consensus reference state. The last section of the chapter presents consensus algorithm for cases where desired relative state deviations among individual systems are also introduced along with a time-varying consensus reference state.

Chapter 4 presents discussion about consensus algorithms for double-integrator dynamics, or 2nd order dynamics. Formal analysis of interaction topologies that allow consensus for 2nd order dynamics is highlighted. A fundamental consensus algorithm is proposed, and conditions under which consensus is reached for fixed and changing interaction topologies are derived. Consensus algorithm, that takes bounded control effort into account, and that, without the requirement for measurements of relative information state derivatives, are also proposed.

Extending the cases discussed in Chapter 4, the subject of Chapter 5 is about consensus algorithms for 2nd order dynamics to a reference model. The discussion begins with algorithms that make the time derivatives of information states track a

certain reference, with and without coupling between neighbors' information states time derivatives. Then, it proceeds with algorithms that make both information states and their time derivatives track a reference model. Three possible cases are discussed: system with fully-accessed reference model, system with leader-following scheme where the reference model is only available to one individual system, and general case system where the reference model may be available to one or multiple individuals.

Chapter 6 discusses algorithms for attitude consensus in a system of rigid bodies. Three problem cases are explored for the subject. The first problem is a system of multiple rigid bodies which are to align their attitudes and achieve final angular velocities that equal to zero. The second problem is a system of multiple rigid bodies which are required to have their attitudes converge to a constant reference value while aligning their attitudes during transition and achieve final angular velocities that equal to zero, without the requirement for absolute and relative angular velocities measurements. The third case is a system of multiple rigid bodies which are required to have their angular velocities converge to reference value while aligning their attitude during transition.

Chapter 7 discusses problem extensions of consensus algorithms for system of multiple rigid bodies' attitude dynamics. Algorithms to maintain relative attitudes and angular velocities are presented, with both fixed and time-varying reference attitude and angular velocity considered. In the following section, the discussion is about algorithms to track a reference attitude. Reference attitude tracking problems, represented by Euler parameters and modified Rodriguez parameters, are discussed. Algorithms for system with full access and partial access to the reference attitude are presented.

In Chapter 8, consensus-based design methodologies for distributed multivehicle cooperative control are introduced. In the first section, beginning with explanation about the nature of cooperative control problem for multivehicle system, the author introduces and describes the ideas on which his approach to cooperative control is based. The outline of his approach is also presented. The following section consists of explanation about how the distributed cooperative control problems are formulated. Also in this section, explanation about the presence of coupling among the vehicles in cooperative control as a way to classify the classes of problems in cooperative control problems, which are divided into 4 cases according to the strength or degree of the coupling. The next two sections discuss the approach to cooperative control problems with and without an optimization objective. For that with an optimization objective, an example is discussed and the approach is outlined into 4 steps: identifying and quantifying cooperation constraint and objective, determining coordination variables and function, formulating the optimization problem and designing centralized cooperative strategy to solve it, and decentralizing the cooperation algorithm. And for that without optimization objective, the procedure is simplified, with two cases being discussed. However, discussion about applications of these approaches is presented in the following six chapters. An overview of literature on formation control and multi-UAV cooperation is presented at the end of the chapter.

Two experimented applications based on the approach to cooperative control without optimization objective as discussed in Chapter 8 are presented in Chapter 9: rendezvous problem, and axial alignment problem. The experiments are carried out on a test-bed called Mobile Actuator and Sensor Network, or the MASnet platform.

Chapter 10 discusses experimented application of consensus-based design to formation control of multiple mobile robots with a virtual leader. The experiments are carried out on a testbed consisting of five AmigoBots and two Pioneer 3-DXs, the USU Mobile Robots Laboratory's mobile robots platform. The proposed strategy is unified yet distributed formation control architecture that is able to accommodate an arbitrary number of subgroup leaders and arbitrary information flow among the robots. The kinematic models of the mobile robots are taken into consideration. Detailed discussion about the strategy is presented in the first section. In the following section, three experimentations on the proposed formation control algorithm are presented: formation control with a single sub-group leader, formation control with multiple sub-group leaders, and formation control with dynamically changing sub-group leaders and interaction topologies.

Chapter 11 presents applications which are continuation of those presented in Chapter 10, where formation control schemes take dynamic couplings among the mobile robots into consideration. In the first two sections of the chapter, problem and objective formulations are thoroughly analyzed. In the following chapter, the control strategies are derived with three case variants. The first strategy is coupled dynamics formation control, which takes in relative positions and relative velocities between neighboring robots. The second is coupled dynamics formation control with passivity-based inter-robot damping, which basically the same as the first one but without taking in the relative velocities between neighboring robots in the algorithm. The third strategy is saturated control, which is the modification of the first strategy that considers actuators' saturation constraints. The experiments are carried out on three mobile robots of Brigham Young University's Multiple Agent Intelligent Coordination and Control (MAgICC) platform.

Chapter 12 discusses the application of coordinated control design deep spacecraft formation maneuvering. The proposed strategy is the use of decentralized formation control scheme that is built on the combination of consensus algorithms and the virtual structure approach, which is expected to be able to handle system with large number of spacecraft, or where communication among the spacecrafts is limited. The problem formulation is discussed in the first section consisting reference frames, individual spacecraft desired state, and spacecraft dynamics. The following section presents both, in comparison, centralized and decentralized architecture to emphasize the

feature of the proposed decentralized architecture scheme. In the next section, the required tasks that need to be carried out by the scheme are discussed: to control each individual spacecraft to track its desired state defined by the virtual structure, and to drive each virtual structure instantiation into consensus to achieve the desired formation pattern. The experimentation for the control scheme is carried out by simulation performing a scenario where a group of nine spacecrafts perform a group maneuver while maintaining their formation.

In Chapter 13, an experimented simulation carried out to explore the feasibility of using team of multiple low altitude short endurance (LASE) UAVs to cooperatively monitor and track the propagation of forest fires is presented. The chapter begins with problem statement, followed by a summary about fire perimeter tracking by individual UAV, and derivation of latency minimization and distributed monitoring algorithm. The model used for fire was developed using the Ecological Model for Burning in the Yellowstone Region (EMBYR).

In Chapter 14, discussion about a cooperative control strategy for aerial surveillance tested on a team of UAVs is presented. The cooperative control strategy is the one described in Section 8.3. Two problem variants are considered in this experimentation: persistent imaging, where a team of UAVs equipped with imaging sensors are tasked to persistently image a known target by performing fly-by over it at a regular interval, and cooperative identification, where the team is required to fly over a target simultaneously from several different directions.

Appendix A lists abbreviations and mathematical notations that occur throughout the book.

Appendix B presents the Graph theory, a study of mathematical structures used to model pair-wise relations between objects from certain collection. This subject has been attracting many famous mathematicians since the 18th century BC, at the latest. In this appendix, selected concepts and properties of Graph are summarized.

Appendix C presents the theory of Matrices. Concepts and properties of matrices are summarized. The summary is limited to those used in the main content of the book.

Appendix D entitles Rigid Body Attitude Dynamics. It presents summary about rigid body's angular kinematics and dynamics. The author chooses quaternion expression in deriving rigid body's kinematic and dynamic equations.

Appendix E and Appendix F present the Linear System theory and the Nonlinear System theory, respectively. They present the summaries about selective subjects regarding their basic concepts and their properties.

III. Assessment

The organization of this book that is to start with more basic theories and analyses then to proceed with more complex and difficult ones is the strength point of this book. Subjects and concepts that are basic to main subject are placed in appendices, reducing the necessities for the reader to consult external references regarding prerequisite materials. The reader can then proceed more swiftly throughout the book.

The book generally has a good balance between theories and applications. Theoretical aspects of the works done and reported in the book are adequately presented.

Illustrative pictures used throughout the book are very useful in conveying concepts, dimensions, and results, especially in discussing the concept of graph. Notations and symbols are carefully used as to not conflicting one with another while keeping the amount of them minimal. The author uses mathematical expressions in line with text in various occasions. It may be considered as an efficient way in conveying ideas, arguments, etcetera, but for some cases, where the expressions are not simple, it reduces readability.

In conclusion, this book provides valuable discussions on cooperative control of multiple vehicle systems. There is no doubt that control systems researchers in academia, industries and government laboratories will be rewarded from reading this book and their insights enriched by the authors' perspectives.