Machine Behavior Design And Analysis

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A Consensus Perspective

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To our ancestors and parents, as always

Preface

Multi-agent systems have attracted lots of research interest in the recent decades. Consensus is a fundamental issue in distributed cooperative control of multi-agent systems and distributed computing, which has broad applications, such as formation control. Such topics could be included in an emerging interdisciplinary field of machine behavior: the scientific study of behavior exhibited by intelligent machines, which was recently discussed in a review article entitled "Machine behaviour" written by Rahwan et al. published in *Nature*.

Decision making is an important component of machine behavior. The investigations on cooperative control and computing have shown that via cooperations, a team of simple agents can perform complex tasks. In this book, we show the design and analysis of machine behaviors from a consensus perspective. We discuss second-order and high-order min-consensus. A very interesting topic regarding the link between consensus and path planning is also included. We show that a biased min-consensus protocol can lead to the path planning phenomenon, which means that the complexity of shortest path planning can emerge from a perturbed min-consensus protocol, which as a case study may encourage researchers in the field of distributed control to rethink the nature of complexity and the distance between control and intelligence. We also illustrate the design and analysis of consensus protocols for nonlinear multi-agent systems derived from an optimal control formulation, which do not require solving a Hamilton–Jacobi–Bellman (HJB) equation.

Most of the materials in this book are derived from the authors' papers published in journals, such as *IEEE Transactions on Automatic Control*. To make the contents clear and easy to follow, in this book, each part (and even each chapter) is written in a relatively self-contained manner. Meanwhile, in each chapter, we provide steps of algorithm design, theoretical analysis, and numerical examples.

This book is divided into the following eight chapters.

Chapter 1: In this chapter, we present some background knowledge about the topics discussed in this book.

Chapter 2: In this chapter, a second-order min-consensus protocol is presented with provable convergence. Under certain conditions, the protocol can guarantee

global asymptotic min-consensus, even for the case with jointly connected communication graphs. An illustrative example is also presented.

Chapter 3: In this chapter, two novel distributed protocols are presented to address the consensus of high-order discrete-time multi-agent systems. By the presented consensus protocols, each agent only needs to transmit the value of a real-value variable to neighbor agents regardless of the order of agent dynamics. Theoretical analysis shows that the presented protocols guarantee asymptotic consensus of the agent states in different cases of communication graphs, including jointly connected ones. Various simulative examples about the protocols are also presented.

Chapter 4: In this chapter, a perturbed continuous-time min-consensus protocol is presented. It is shown that the complex behavior of shortest path planning can emerge from the protocol. It is proved that the graph dynamics is convergent and its equilibrium is equivalent to a corresponding shortest path solution. An illustrative simulation on a small scale graph is provided to show the convergence of the biased min-consensus dynamics to shortest path solution over the graph. The applications to path planning in a maze and the robot complete coverage are also presented.

Chapter 5: In this chapter, a discrete-time biased min-consensus protocol is presented, which is of finite-time convergence and is designed via modifying an existing min-consensus protocol. The convergence of the protocol is analyzed under time delay and a synchronous state update. It is shown that a complex behavior that can address shortest path planning on a graph emerges from this consensus protocol. To show the scalability and efficiency of the presented protocol, it is applied to large-scale maze solving on a maze map. In addition, we also present an application of the presented protocol to address the complete coverage problem, which further demonstrates the potential of biased min-consensus in robotic applications.

Chapter 6: In this chapter, a unified neural network scheme based on biased min-consensus is presented for solving the classical shortest path problem and the generalized shortest path problem, which are highly nonlinear. Particularly, the generalized shortest path problem is more complex than the classical shortest path problem since it requires finding a shortest path among the paths from a vertex to all the feasible destination vertices. Different from existing results, inspired by the optimality principle of Bellman's dynamic programming, we formulate the two types of shortest path problems as linear programs with the decision variables denoting the lengths of possible paths. Then, biased consensus neural networks are adopted to solve the corresponding linear programs in an efficient and distributed manner. Theoretical analysis guarantees the performance of the presented scheme. In addition, two illustrative examples are presented to validate the efficacy of the presented scheme and the theoretical results. Moreover, an application to mobile robot navigation in a maze further substantiates the efficacy of the presented scheme.

Chapter 7: In this chapter, a unified framework is proposed for designing distributed control laws to achieve the distributed consensus of linear and nonlinear multi-agent systems. The consensus problem is formulated as a receding-horizon dynamic optimization problem with an integral-type performance index subject to the dynamics of the considered multi-agent system. Different from conventional

optimal control that solves HJB equation numerically in high dimensions, we present a suboptimal solution with analytical expressions by utilizing Taylor expansion for prediction along time and give the corresponding distributed control law in an explicit form. Theoretical analysis shows that the proposed control laws can guarantee exponential and asymptotical stability of the multi-agent systems. It is also proved that the proposed suboptimal control laws tend to be optimal with time. Illustrative examples are also presented.

Chapter 8: In this chapter, the near-optimal distributed consensus of high-order nonlinear multi-agent systems consisting of heterogeneous agents is investigated, which is the extension of Chap. 7. Under the condition that the dynamics of all agents are fully known, a nominal near-optimal protocol is presented via making approximation of the performance index. For the situation with fully unknown system parameters, sliding-mode auxiliary systems, which are independent for different agents, are built to reconstruct the input-output properties of agents. Based on the sliding-mode auxiliary systems, an adaptive near-optimal protocol is finally presented to control high-order nonlinear multi-agent systems with fully unknown parameters. Theoretical analysis shows that the presented protocols can simultaneously guarantee the asymptotic optimality of the performance index and the asymptotic consensus of multi-agent systems. An illustrative example is given to show the performance.

In summary, this book mainly focuses on min-consensus and related topics. We discuss min-consensus protocols, biased min-consensus and the complex behavior (i.e., path planning) emerging from biased min-consensus protocols, and consensus protocols for nonlinear multi-agent systems via near-optimal adaptive control. This book is written for graduate students and academic and industrial researchers in the field of distributed computing, consensus, and distributed control. We hope that this book will benefit the readers.

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December 2019

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Acronyms

ARX	Auto-regressive exogenous
ASV	Auxiliary state variable
BMC	Biased min-consensus
FLOPs	Floating point operations
HJB	Hamilton–Jacobi–Bellman