Notice of the Final Oral Examination
for the Degree of Doctor of Philosophy

of

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“Analysis and Synthesis of Distributed Control Systems under Communication Constraints”

Department of Mechanical Engineering

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Engineering and Computer Science Building
Room 468

Supervisory Committee:
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Dr. Daniela Constantinescu, Department of Mechanical Engineering, UVic (Member)
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Abstract

With the help of rapidly advancing communication technology, control systems are increasingly integrated via communication networks. Networked control systems (NCSs) bring significant advantages such as flexible and scalable structures, easy implementation and maintenance, and efficient resources distribution and allocation. NCSs empowers to finish some complicated tasks using some relatively simple systems in a collaborated manner. However, they also have some challenges and constraints subject to the imperfection of communication channels. In this thesis, the stabilization problems and the performance limitation problems of control systems subject to networked-induced constraints are studied.

Overall, the thesis mainly includes two parts: 1) Consensus and consensusability of multi-agent systems (MASs); 2) Delay margins of NCSs. Chapter 2 and Chapter 3 deal with the consensus problems of MASs, which aim to properly design the control protocols to drive the group of agents converge to a same state. Chapter 4 and Chapter 5 focus on the consensusability analysis, exploring how the dynamics of the agents and the networked induced constraints impact the overall systems for achieving consensus. Chapter 6 pays attention to the delay margins of discrete-time linear time-invariant (LTI) systems, studying how the dynamics of the plants limit the time delays that can be tolerant by LTI controllers.

In Chapter 2, the leader-following consensus problem of MASs with general linear dynamics and arbitrary switching topologies is considered. The MAS with arbitrary switching topologies is formulated as a switched system. Then the leader-following consensus problem is transformed to the stability problem of the corresponding switched system. A necessary and sufficient consensus condition is derived. The condition is also extended to MASs with time-varying delays.

In Chapter 3, the consensus problem of MASs with general linear dynamics is studied. Motivated by the multiple-input multiple-output (MIMO) communication technique, a general framework is considered in which different state variables are exchanged in different independent communication topologies. This novel framework could improve the control system design flexibility and potentially improve the system performance. Fully distributed consensus protocols are proposed and analyzed for the settings of fixed and switching multiple topologies. The protocols can be applied using only local information. And the control gains can be designed depending on the dynamics of the individual agent. By transforming the overall MASs into cascade systems, necessary and sufficient conditions are provided to guarantee the consensus under fixed and switching state-variables-dependent topologies, respectively.

Chapter 4 investigates the consensusability problem for MASs with time-varying delays. The bounded delays can be arbitrarily fast time-varying. The communication topology is assumed to be undirected
and fixed. Considering general linear dynamics under average state protocols, the consensus problem is then transformed into a robust control problem. Sufficient frequency domain criteria are established in terms of small-gain theorem by analyzing the delay dependent gains for both continuous-time and discrete-time systems. The controller synthesis problems can be solved by applying the frequency domain design methods.

The consensusability problem of general linear MASs considering directed topologies are explored from a frequency domain perspective in Chapter 5. By investigating the properties of Laplacian spectra, a consensus criterion is established based on the stability of several complex weighted closed-loop systems. Furthermore, for singleinput MASs, frequency domain consensusability criteria are proposed on the basis of the stability margins, which depend on the $H_\infty$ norm of the complementary sensitivity function determined by the agents’ unstable poles. The corresponding design procedure is also developed.

Chapter 6 studies the delay margin problem of discrete-time LTI systems. For general LTI plants with multiple unstable poles and nonminimum phase zeros, we employ analytic function interpolation and rational approximation techniques to derive bounds on delay margins. Readily computable and explicit lower bounds are found by computing the real eigenvalues of a constant matrix, and LTI controllers can be synthesized based on the $H_\infty$ control theory to achieve the bounds. The results can be also consistently extended to the case of systems with time-varying delays. For first-order unstable plants, we also obtain bounds achievable by proportional-integral-derivative (PID) controllers, which are of interest to PID control design and implementation. It is worth noting that unlike its continuous-time counterpart, the discrete-time delay margin problem being considered herein constitutes a simultaneous stabilization problem, which is known to be rather difficult. While previous work on the discrete-time delay margin led to negative results, the bounds developed in this chapter provide instead a guaranteed range of delays within which the delayed plants can be robustly stabilized, and in turn solve the special class of simultaneous stabilization problems in question.

Finally, in Chapter 7, the thesis is summarized and some future research topics are also presented.