INSTITUT FÜR
MECHANIK UND
MECHATRONIK
Mechanics & Mechatronics

Division of Control and
Process Automation

Technische Universität Wien
Institute of Mechanics and Mechatronics
Getreidemarkt 9/BA/E325-04
1060 Vienna, Austria

Priv.-Doz. Dr. Alexander Schirrer

T: +43-1-58801-325521
alexander.schirrer@tuwien.ac.at
www.mec.tuwien.ac.at

CTU in Prague - Czech Technical University in Prague
Faculty of Electrical Engineering
Office for Science and Research
Ing. Marie Duchoslavová
Technicka 2
166 27, Prague 6
Czech Republic

Ihre Zeichen, Ihre Nachricht vom	Unsere Zeichen	, Bearbeiter
Report on thesis of Š. Knotek	Report thesis Knotek	A. Schirrer

Vienna, 27.12.2020

Report on the dissertation thesis of Štefan Knotek

Dear madam or sir,

Following your kind invitation I have reviewed the dissertation thesis "Consensus and Synchronization in Distributed Estimation and Adaptive Control" submitted by Ing. Štefan Knotek in the field "Control Engineering and Robotics" at the Faculty of Electrical Engineering, Czech Technical University in Prague.

The thesis tackles core estimation and control problems of distributed control systems in a novel and appealing way and provides significant additions to the state of the art. It is structured clearly and written in a well-understandable and accessible way. This report addresses the main aspects of the thesis' evaluation as structured below.

Relevance The thesis subject is highly relevant to the current research needs in the scientific control community. Distributed estimation and distributed adaptive control of multi-agent systems are thriving areas of research, especially in the context of novel, growing applications such as the Internet-of-Things, smart distributed and cost-effective devices with multiple sensors and the ability to interact autonomously with other devices. The need for robust, well-performing strategies for distributed sensing and sensor fusion as well as control is a highly relevant topic to create scalable digital ecosystems. It is essential for such strategies to be able to rely only on local and neighbor information and not need any centralized, global knowledge during design or execution of estimation and control laws. The present thesis takes important steps into that direction and provides usable tools, underpinned by rigorous stability guarantees and convergence results of the consensus and synchronization tasks in both, distributed estimation and distributed adaptive control use cases.

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Fulfillment of main objectives The thesis sets out to answer two related yet complementary research questions: (1) providing a distributed estimation scheme for large-scale systems, and (2) provide a fully distributed adaptive control protocol for multi-agent consensus and synchronization on directed communication networks. Each research question is specified with requirements for the proposed solutions, and both research questions have been answered accurately and in appropriate detail. While the author admits that in the estimation approach the requirement of small communication effort is only partially investigated and deeper studies on this matter are of interest, the thesis also contains additional algorithms as alternative approaches to estimate the references of the coupling gains in the adaptive control scheme. These algorithms go well beyond the original set of goals of the thesis, but their inclusion fits well into the topic and improves the coverage and usability of the thesis and is thus well justified. The objectives of the work have thus been fulfilled entirely and comprehensively.

Appropriateness of methods The choice of methods used in the thesis are up to date and appropriate: starting with a thorough account of the state-of-the-art, the research gaps are clearly identified and appropriate specific designs, methods and algorithms are proposed. These are rigorously investigated - stability and convergence in the estimation part is studied via structured Lyapunov functions, the covariance of the observation error is characterized and bounded using statistical arguments, and paralleles with the classical Kalman filter are studied. Lyapunov theory is applied to study stability in the adaptive leaderless and leader-following consensus control structures, and two approaches for the estimation of references of the coupling gains are proposed. Numerical simulations validate and illustrate the theoretical results.

Main results and contributions The thesis addresses two complementary topics organized via two corresponding research questions. For the first research question, a distributed estimator for large-scale sensor networks is developed. Combining ideas of the existing state of the art approaches in distributed Kalman filters and distributed Luenberger observers, a generally sub-optimal distributed estimator structure is devised which shows key properties that have not been available in their entirety in the state of the art. Specifically, process and measurement noises are considered, redundant and communication-only nodes are considered, only partial observability from each single-agent's perspective is required, directed communication graphs are considered, and covariance information does not need to be communicated, hence reducing communication effort. A fully distributed architecture is proposed which requires only local and neighbor information in design and operation of the estimation algorithm. It does, however still need some global (centralized) information characterized by design parameter bounds. For the second research question, a distributed adaptive consensus protocol is developed. A core requirement is a fully distributed structure, understood here as the total lack of dependencies on global (centralized) information. The entire conceptualization, design and operation of the consensus protocols can be carried out by local and neighbor information only. This is achieved by the notion of coupling gain dynamics (allowing the coupling gains to decay to estimated reference values), as well as estimation mechanisms for these reference values of the coupling gains which finally allow for a fully distributed implementation of the protocol. Both the cooperative regulator and tracker problems are addressed on general directed communication graphs. The formulation shows good robustness against noise and disturbances. These developments

are accompanied with rigorous proofs of stability and convergence of the state estimates as well as uniform ulitmate boundedness of the agents' trajectories in the case of the adaptive consensus protocol variants. Simulation examples show the validity of the theoretical results and illustrate their implementation. These contributions are highly relevant for estimation and control in distributed settings, and their excellent quality is evidenced additionally by the two underlying main publications which have been accepted in renowned, scientific, peer-reviewed control journals.

Importance for further development of science Not only is the thesis of high direct scientific value and pushes the boundaries of current knowledge in the field, it also serves the scientific community in its tutorial value and its well-accessible and in-depth explanation of the state-of-the-art in the respective domains. The state-of-the-art is clearly collected and presented, giving a compact and precise account on the major approaches, methods and algorithms. This allows to appreciate their strengths and limitations, and the thesis contributions are clearly positioned with respect to this surveyed state-of-the-art. Finally, an outlook to possible follow-up research is given in a structured way, particularly hinting at the performance potential if the proposed algorithms were refined and/or combined. Such combined architecture is expected to remove the last dependencies on centralized (meta-)information in terms of a parameter bound which is still needed in the design of the proposed estimator, but this requires a subsequent, thorough and complex theoretical investigation which is out of scope of this thesis. Despite the complexity of the subject, the thesis does an excellent job to clearly lay out the contributions, its strengths and limitations and requirements to a general control readership.

Creative scientific work The thesis represents a creative, thoughtful and precise piece of scientific work. One particularly interesting feature is the logical and elegant overarching bridge that connects the two topic groups (clearly structured by the two research questions and their respective underlying journal publications). This arc is spanned successfully from the distributed estimation treatment to the distributed adaptive control contribution. The result is a highly applicable thesis with hands-on algorithms as well as rigorous results covering the broad topic successfully and providing exceptional scientific value and high accessibility.

The author of the thesis proved to have an ability to perform research and to achieve scientific results. I do recommend the thesis for presentation with the aim of receiving a Ph.D. degree.

Yours sincerely,

Alexander Schirrer

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