

Invited Session Proposal: Distributed Estimation over Sensor Networks

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1 Session Organizers

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2 Description of the topic

The recent technological advances in wireless communication and decreasing in cost and size of electronic devices, are promoting the appearance of large inexpensive interconnected systems, each with computational and sensing capabilities. These complex systems of systems can be used for monitoring very large scale areas with fine resolution. However, collecting measurements from distributed wireless sensors nodes at a single location for on-line data processing may not be feasible due to several reasons among which long packet delay (e.g. due to multi-hop transmission) and/or limited bandwidth of the wireless network, due e.g. to energy consumption requirements.

This problem is apparent in wireless ad-hoc sensor networks where information needs to be multi-hopped from one node to another using closer neighbors. Therefore there is a growing need for in-network data processing tools and algorithms that provide high performance in terms of on-line estimation while (i)

reducing the communication load among all sensor nodes and (ii) being very robust to sensor node failures or replacements and packet losses.

Distributed estimation plays of course an important role in many practical problems connected to sensor networks among which distributed monitoring, tracking and control.

Distributed estimation have attracted a lot of attention since the late sixties; however the traditional way to face this problem did not yield practical solutions for large number of agents.

In the recent years we have witnessed, mainly due to the reasons mentioned above, a renewed interest towards this class of problems. Recently studied consensus algorithms, commonly used in the theory of Distributed Algorithms as an efficient method for information fusion, are providing, in conjunction with the classical “Kalman-like” approach, useful tools to tackle distributed estimation problems.

The purpose of this session is both to promote discussion among researchers actively working in distributed estimation and to provide an up-to-date overview of the research directions and advances in the field.

The session will be composed as follows: there will be four contributions discussing several aspects of distributed Kalman filtering, including effect of packet losses, estimation of time varying signals and bandwidth limitation.

One paper will discuss estimation of time delays in asymmetric wireless communication networks. This is instrumental to time-synchronization, which is essential for both distributed estimation and control.

Last but not least there will be a contribution discussing the role of network topology for distributed estimation. In particular the papers discusses how the network routing strategy can be controlled as to stay within desired error bounds while minimizing transmission energy.

3 List and description of the proposed session contributions

1. *Distributed Kalman filtering: Theory and experiments*
Peter Aliksson and Anders Rantzer

Paper contribution:

This paper addresses both the theoretical problem of distributed Kalman filtering and implementational issues encountered when the algorithm was experimentally evaluated. By distributed we refer to a scenario when all nodes in the network desire an estimate of the full state of the observed system and there is no centralized computation center.

To reduce bandwidth requirements of individual nodes, estimates instead of measurements are communicated between neighboring nodes. A new estimate is then formed as a weighted average of the neighboring estimates. The weights are optimized to yield a small estimation error covariance in

stationarity. The minimization can be done off line thus allowing only estimates to be communicated. The advantage of communicating estimates instead of measurements becomes more evident when the number of nodes exceeds the size of the state vector to be estimated.

To investigate how the proposed algorithm performs in an uncertain environment where, for example packets are lost and different nodes are not synchronized in time an experimental testbed was constructed. The scenario chosen is one where seven nodes in a sensor network estimate the position of a mobile robot using ultrasound.

2. *Distributed Kalman Filtering: Consensus Filtering and Packet-loss issues in Sensor Networks*

Reza Olfati-Saber

Paper contribution:

In this paper, we introduce a novel distributed Kalman filtering (DKF) algorithm in sensor networks for distributed state estimation and target tracking. Unlike its predecessor algorithm presented in CDC-ECC 05, this DKF algorithm consists of identical high-pass consensus filters for distributed fusion of sensor data and covariance information. This algorithm enables a sensor network to act as a collective observer for a process that is not observable by an individual sensor, or a small group of sensors. We discuss the reasons behind the modifications of the DKF algorithm as well as asynchronous communication, packet-loss, and time-scaling issues involved in design and analysis of consensus filters for sensor networks. The algorithm only requires single-hop communication between a sensor and its neighbors. Simulation results are provided that demonstrate the effectiveness of the DKF algorithm for distributed target tracking.

3. *Adaptive Distributed Estimation over Wireless Sensor Networks with Packet Losses*

A. Speranzon, C. Fischione, B. Johansson, K.H. Johansson

Paper contribution:

An adaptive strategy for distributed estimation of a time-varying signal measured by a wireless sensor network is presented. A stable filter is derived in which time-varying weights are computed to minimize the estimation error covariance. We discuss trade-offs between optimality and computational costs. The paper extends earlier results by the authors to the case of packet losses. Robustness of the filter to common models of packet loss is studied.

4. *Distributed Kalman filtering using consensus strategies*

Ruggero Carli, Alessandro Chiuso, Luca Schenato and Sandro Zampieri

Paper contribution:

In this paper, we consider the problem of estimating the state of a dynamical system from distributed noisy measurements. Each agent constructs

a local estimate based on its own measurements and estimates from its neighbors. Estimation is performed via a two stage strategy, the first being a Kalman-like measurement update which does not require communication, and the second being an estimate fusion using a consensus matrix.

In particular we study the interaction between the consensus matrix, the number of messages exchange per sampling time, and the Kalman gain.

We prove that optimizing the consensus matrix for fastest convergence and using the centralized optimal gain is not necessarily the optimal strategy if the number of message exchange per sampling time is small. Moreover, we prove that under certain conditions the optimal consensus matrix should be doubly stochastic. We also provide some numerical examples to clarify some of the analytical results.

5. *On the effect of asymmetric communication on distributed time synchronization*

Prabir Barooah, Joao P. Hespanha, and Ananthram Swami

Paper contribution:

Time-synchronization is an important problem for sensor and actuator networks. For feedback control over communication networks to be a reality, it is important that the clocks of different nodes connected by a communication network be synchronized with one another. This synchronization requires the accurate estimation of the difference between local clock times and a global time reference for all the nodes in the network. Several distributed algorithms have been proposed recently to solve this problem. Noisy measurements of the difference of local times between pairs of neighboring nodes are collected. The algorithms then iteratively compute the optimal estimates (minimum variance among all linear unbiased estimates) of the difference between the local times and the global reference.

However, these algorithms require symmetric (bidirectional) communication between nodes. In ad-hoc wireless networks, communication between pair of nodes may be asymmetric (uni-directional). Motivated by this, we examine the behavior of these algorithms in the presence of uni-directional communication links.

We first show that in the presence of asymmetric communication links, these algorithms do not converge to the optimal estimate in general. In fact, we prove that with a linear distributed algorithm that is constrained to use only local information, it is impossible to converge to the optimal estimate. However, they converge to an unbiased estimate provided certain connectivity property of the communication graph is satisfied. We characterize the resulting estimate and its error covariance that the algorithm produces upon convergence. Asymmetric communication results in another distinct behavior of the algorithms compared to the symmetric

case that is important in practice. When the measurements corresponding to the uni-directional links are ignored, the variance of the estimates may be lower than what is otherwise obtained by using all the available measurements. This is in contrast to the bidirectional case, where more measurements (no matter how noisy) always leads to better estimates.

6. *Change sensor topology when needed: how to efficiently use system resources in control and estimation over wireless networks*
Ling Shi, Richard Murray and Karl Henrik Johansson

Paper contribution:

New paradigms are needed for control over large networks of wireless sensors and actuators in order to efficiently utilize system resources. In this paper we consider a situation when feedback control loops are formed locally to detect, monitor, and counteract disturbances that hit a plant at random instances in time and space. A sensor node that detects a disturbance dynamically forms a local network of sensors and fuse the data into a state estimate. The routing of sensor data is optimized such that the overall transmission energy is minimized but enables a guaranteed level of estimation accuracy. The routing protocol and estimation algorithm are described in detail. The application to a distributed control problem is illustrated through an example.