52. IWK

Internationales Wissenschaftliches Kolloquium
International Scientific Colloquium

PROCCEDINGS | **10 - 13 September 2007**

FACULTY OF COMPUTER SCIENCE AND AUTOMATION

COMPUTER SCIENCE MEETS AUTOMATION

VOLUME I

Session 1 - Systems Engineering and Intelligent Systems
Session 2 - Advances in Control Theory and Control Engineering
Session 3 - Optimisation and Management of Complex Systems and Networked Systems
Session 4 - Intelligent Vehicles and Mobile Systems
Session 5 - Robotics and Motion Systems

TECHNISCHE UNIVERSITÄT
ILMENAU

Bibliografische Information der Deutschen Bibliothek
Die Deutsche Bibliothek verzeichnet diese Publikation in der deutschen Nationalbiografie; detaillierte bibliografische Daten sind im Internet über **http://dnb.ddb.de** abrufbar.

ISBN 978-3-939473-17-6

Impressum

Herausgeber: Der Rektor der Technischen Universität Ilmenau
Univ.-Prof. Dr. rer. nat. habil. Peter Scharff

Redaktion: Referat Marketing und Studentische Angelegenheiten
Kongressorganisation
Andrea Schneider
Tel.: +49 3677 69-2520
Fax: +49 3677 69-1743
e-mail: kongressorganisation@tu-ilmenau.de

Redaktionsschluss: Juli 2007

Verlag:
Technische Universität Ilmenau/Universitätsbibliothek
Universitätsverlag Ilmenau
Postfach 10 05 65
98684 Ilmenau
www.tu-ilmenau.de/universitaetsverlag

Herstellung und Auslieferung: Verlagshaus Monsenstein und Vannerdat OHG
Am Hawerkamp 31
48155 Münster
www.mv-verlag.de

Layout Cover: www.cey-x.de

Bezugsmöglichkeiten: Universitätsbibliothek der TU Ilmenau
Tel.: +49 3677 69-4615
Fax: +49 3677 69-4602

Preface

Dear Participants,

Confronted with the ever-increasing complexity of technical processes and the growing demands on their efficiency, security and flexibility, the scientific world needs to establish new methods of engineering design and new methods of systems operation. The factors likely to affect the design of the smart systems of the future will doubtless include the following:

- As computational costs decrease, it will be possible to apply more complex algorithms, even in real time. These algorithms will take into account system nonlinearities or provide online optimisation of the system's performance.
- New fields of application will be addressed. Interest is now being expressed, beyond that in "classical" technical systems and processes, in environmental systems or medical and bioengineering applications.
- The boundaries between software and hardware design are being eroded. New design methods will include co-design of software and hardware and even of sensor and actuator components.
- Automation will not only replace human operators but will assist, support and supervise humans so that their work is safe and even more effective.
- Networked systems or swarms will be crucial, requiring improvement of the communication within them and study of how their behaviour can be made globally consistent.
- The issues of security and safety, not only during the operation of systems but also in the course of their design, will continue to increase in importance.

The title "Computer Science meets Automation", borne by the 52nd International Scientific Colloquium (IWK) at the Technische Universität Ilmenau, Germany, expresses the desire of scientists and engineers to rise to these challenges, cooperating closely on innovative methods in the two disciplines of computer science and automation.

The IWK has a long tradition going back as far as 1953. In the years before 1989, a major function of the colloquium was to bring together scientists from both sides of the Iron Curtain. Naturally, bonds were also deepened between the countries from the East. Today, the objective of the colloquium is still to bring researchers together. They come from the eastern and western member states of the European Union, and, indeed, from all over the world. All who wish to share their ideas on the points where "Computer Science meets Automation" are addressed by this colloquium at the Technische Universität Ilmenau.

All the University's Faculties have joined forces to ensure that nothing is left out. Control engineering, information science, cybernetics, communication technology and systems engineering – for all of these and their applications (ranging from biological systems to heavy engineering), the issues are being covered.

Together with all the organizers I should like to thank you for your contributions to the conference, ensuring, as they do, a most interesting colloquium programme of an interdisciplinary nature.
I am looking forward to an inspiring colloquium. It promises to be a fine platform for you to present your research, to address new concepts and to meet colleagues in Ilmenau.

Professor Peter Scharff
Rector, TU Ilmenau

Ch. Ament
Professor Christoph Ament
Head of Organisation

Table of Contents

CONTENTS

Page

1 Systems Engineering and Intelligent Systems

2 Advances in Control Theory and Control Engineering

3 Optimisation and Management of Complex Systems and Networked Systems

4 Intelligent Vehicles and Mobile Systems

5 Robotics and Motion Systems

Paper submitted after copy deadline

2 Advances in Control Theory and Control Engineering

52nd Internationales Wissenschaftliches Kolloquium
Technische Universität Ilmenau
10 – 13 September 2007

P. Hilgers / Ch. Ament

Control in Digital Sensor-Actuator-Networks

ABSTRACT

Due to recent advancements in technology powerful yet small embedded systems can be designed. The usage of wireless communication allows for the set-up of flexible and robust control systems. A model-based design method for distributed control systems without the need of central or fusion nodes is presented. As a means for an appropriate distribution of sensors and actuators and their communication the Gramian matrices can be used. Their properties lead to a data fusion which implements inherent system properties. The combination of these techniques results in a robust communication scheme which uses as little as possible energy for the wireless transceivers but still works within well-defined parameters.

Keywords: sensor-actuator-networks, event-discrete transmission, Gramian matrices

INTRODUCTION

It is generally accepted that the usage of sensor-actuator-networks for control purposes has several advantages if compared to classic centralised control. Many authors refer to this fact, see [1,2,3,4,5,6] to name just a few. This architecture is more flexible when a control system is set up and allows an easy reconfiguration as well as adding or removing network nodes. When using a wireless network the cost for the installation lies well below a wired solution. The recent trends in research and commercial products yield in several logical conclusions: Computing power is available at very little cost in very little space as the advancements in microelectronics go on and on. Small memory chips allow storing amounts of data which was impossible only a few years ago. In the mean time many different wireless communications standards have been developed and make it possible to choose a suitable solution for many applications. Thus, sensor-actuator-networks which are flexible, comparably cheap, and easy to maintain can be designed.

They incorporate the ideas of embedded systems and lately embedded microsystems, as well, which do not rely on electronics only but also the technologies of the MEMS area.

A sensor-actuator-network with embedded microsystems at its network-nodes shall be used to set up a decentralised and robust control system. First, we show how an event-discrete state transmission can be established with multiple state observers. Next, the observability and controllability of systems and their parts using Gramian matrices will be discussed. After that these two parts will be combined to set up an useful distributed estimation scheme which will be completed to a control system.

SYSTEM DESCRIPTION

Consider the following system

$$\begin{aligned} \mathbf{x}(k+1) &= \mathbf{A}\mathbf{x}(k)+\mathbf{B}\mathbf{u}(k)+\mathbf{G}\mathbf{v}(k) \\ \mathbf{z}(k) &= \mathbf{C}\mathbf{x}(k)+\mathbf{w}(k) \end{aligned} \tag{1}$$

which is defined as usual and is assumed to be both observable and controllable.

This central structure shall now be distributed over the whole wireless network in the following manner:

- Each node includes a complete state model.
- Each *sensor* node has got an estimator.
- Each *actuator* node has got its according controller.

The wireless communication has several drawbacks which need to be compensated. Wireless communication is not always guaranteed, is delayed, and uses much more energy when compared to the power consumption of a microcontroller. That leads to the goal of controlling the system without the need to transmit data at every time step. The usage of state models is the main key of the proposed control method which will also counteract the discontinuous nature of this communications means. If the models are all synchronised to the real state of the system or are at least very close to the actual state each actuator is able to operate as needed since its controller is fed by the correct system state. The sensors, however, will be able to transmit their data only if the difference between the estimated state and the measured one is bigger than a certain threshold thus saving energy of unnecessary transmissions.

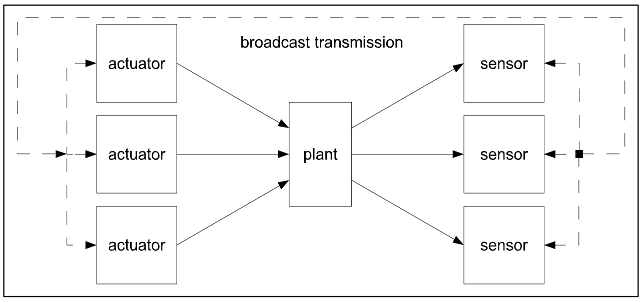

Fig. 1: Schematic description of information flow between sensor and actuator nodes in a distributed control network. Solid lines represent physical connections between actuators, plant, and sensors. Each node is able to transmit data via broadcast to all other nodes which is represented with dashed lines.

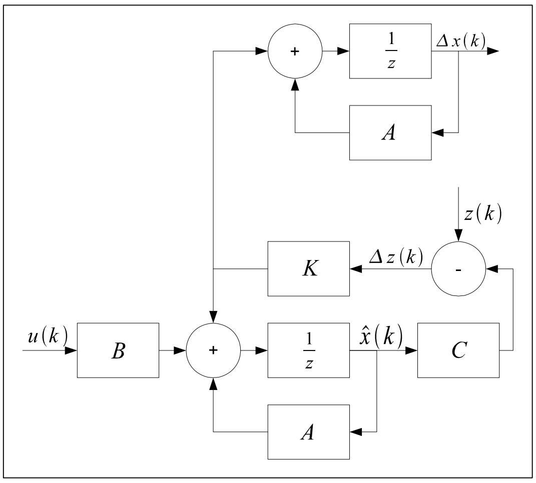

Fig. 2: Simplified Kalman filter with output for comparison with uncorrected model which runs in each sensor node.

Figure 1 shows in principle the connection scheme of a distributed control system. In the centralised case the physical sensors gather their measurements, which are then processed by a Kalman filter. Its state estimate is then used by a controller to give input signals to the actuators which influence the plant. In the simple way of a distributed control network this communication flow is established, as well. Several sensor nodes with their local Kalman filters, which inherently include a state model, gather information from the plant and process them. This is shown in figure 2. The lower part is essentially an uncorrected state model which runs equations (1). $\mathbf{K}$ is the Kalman gain which is computed offline or online according to the standard formula (see [8]). The correction of the model is an additive term: $\mathbf{K}(\mathbf{z}(k)-\mathbf{C}\hat{\mathbf{x}}(k)) = \mathbf{K}\Delta\mathbf{z}(k)$. This yields

$$\hat{\mathbf{x}}(k+1) = \mathbf{A}\hat{\mathbf{x}}(k) + \mathbf{K}(\mathbf{z}(k)-\mathbf{C}\hat{\mathbf{x}}(k)) + \mathbf{B}\mathbf{u}(k) + \mathbf{G}\mathbf{v}(k) = \mathbf{A}\hat{\mathbf{x}}(k) + \mathbf{K}\Delta\mathbf{z}(k) + \mathbf{B}\mathbf{u}(k) + \mathbf{G}\mathbf{v}(k) \tag{4}$$

as state propagation. To account for the difference between the state vector in equations (1) and (4) one has to propagate the correction with the state matrix. This means at each time the difference between an uncorrected model and the Kalman filter estimate is (upper part in figure figure 2)

$$\Delta\mathbf{x}(k+1) = \mathbf{A}\Delta\mathbf{x}(k) + \mathbf{K}\Delta\mathbf{z}(k) + \mathbf{G}\mathbf{v}(k) \tag{5}$$

At each time instant the biggest absolute value of the entries of the difference $\Delta\mathbf{x}$ is computed and compared with a threshold. If the threshold is crossed $\Delta\mathbf{x}$ will be set

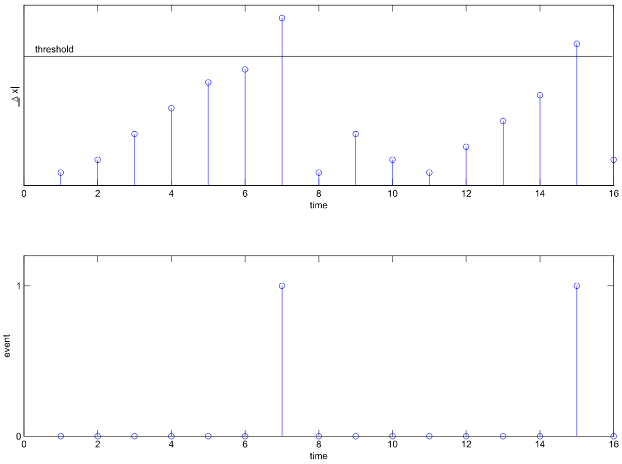

Fig. 3: Generation of transmission events.

to zero and an event will be generated (see figure 3). This event starts the transmission of the state in order to correct all other node models. See [1,7] for further references.

GRAMIAN MATRICES

For a detailed description of the controllability and observability of distributed systems the Gramian matrices can be used. The controllability Gramian $\mathbf{W}_\mathrm{C}$ and the observability Gramian $\mathbf{W}_\mathrm{O}$ are the symmetric, non negative definite matrices which satisfy the following Lyapunov equations, respectively ([9]):

$$\begin{aligned} &\mathbf{A}\mathbf{W}_\mathrm{C} + \mathbf{W}_\mathrm{C}\mathbf{A}^\mathrm{T} + \mathbf{B}\mathbf{B}^\mathrm{T} = 0 \\ &\mathbf{A}^\mathrm{T}\mathbf{W}_\mathrm{O} + \mathbf{W}_\mathrm{O}\mathbf{A} + \mathbf{C}^\mathrm{T}\mathbf{C} = 0 \end{aligned} \tag{6}$$

A full rank n of $\mathbf{W}_\mathrm{C}$ or $\mathbf{W}_\mathrm{O}$ shows a complete controllability or observability, respectively. Otherwise it indicates the controllable or observable subspace. Furthermore, the entries in the matrices indicate how easy or hard it is to control or observe a state. In [9] several properties of the Gramians are discussed. In short these are: The Gramians depend on the state space realisation. However, their product $\mathbf{W}_\mathrm{C} \cdot \mathbf{W}_\mathrm{O}$ does not and can be used for further insight into the system. The Gramians can also be computed with reduced input or output matrices. That is, for single columns j of $\mathbf{B}$ or lines i of $\mathbf{C}$ a corresponding $\mathbf{W}_{\mathrm{C}j}$ and $\mathbf{W}_{\mathrm{O}i}$ can be computed. The sum over all these matrices results in the matrices of the full system.

EVENT-DISCRETE STATE TRANSMISSION AND DATA FUSION

The above mentioned technique of an event-discrete state transmission will now be combined with Gramian data fusion. The different observability properties of different sensor nodes will be taken to fuse all data correctly. When the local threshold of sensor i is crossed two things will be done: $\Delta\mathbf{x}_i(k)$ will be set to zero so that is can be computed correctly in the next time step and the event for state transmission will be generated. This event is transmitted to all actuators and triggers the data fusion.

Data fusion can be done in many different ways. In this work we propose the usage of Gramians as a means and show that this leads to better results than simply taking the average over all measurements. The advantage of this new approach is to exploit the properties of the Gramians. Each sensor has got its respective observability Gramian

$\mathbf{W}_{\mathrm{O}i}$. The transmitted state is multiplied with it so that the data arriving at the actuators is $\mathbf{W}_{\mathrm{O}i} \cdot \hat{\mathbf{x}}$.

The fusing scheme is shown in figure 4. In the case of an event the trigger passes trough the newly arrived data from the according sensor. The current model data is multiplied with the remaining untriggered observability matrices and then summed up. Since all observability sub-matrices sum up to the full matrix a multiplication with the inverse Gramian ensures a proper transformation of these values back into state space. There are two advantages of this fusing scheme: First, at most times sensors will not always trigger an event at the same time. The here proposed fusion deals with this by taking the current model value to substitute the missing sensors. Second, the multiplication with the observability matrices and its inverse make use of the inherent network and system structure. If a sensor can observe a state very well its new information will be given very much weight in the fusion. In the opposite case, if a sensor has no insight in a state during the fusion values close or equal to zero will be multiplied with it and therefore preventing its influence. The usage of these matrices is based on a profound method that relies solely on the model of the system and its precision.

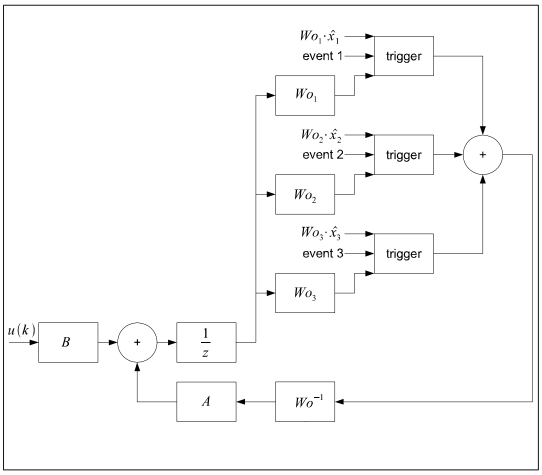

Fig. 4: Data fusion in actuator nodes.

RESULTS

The results of a test system are shown in figures 5 and 6. A small system of a simple plant, three sensors and actuators each was simulated. A classical PI-controller was designed and distributed onto the actuator nodes. Its goal is to bring the system into a desired state. The difference between the desired and actual state is summed up. At the same time the sum of all transmissions between sensor and actuator nodes is recorded. This scheme is repeated for rising threshold values. While the transmissions drop the total error is rising. To show the effectiveness of the Gramian data fusion a system with average value fusion was simulated as well. It can be seen that at a level auf 50% of maximal transmissions the sum of errors is 1.4 time higher when compared to the

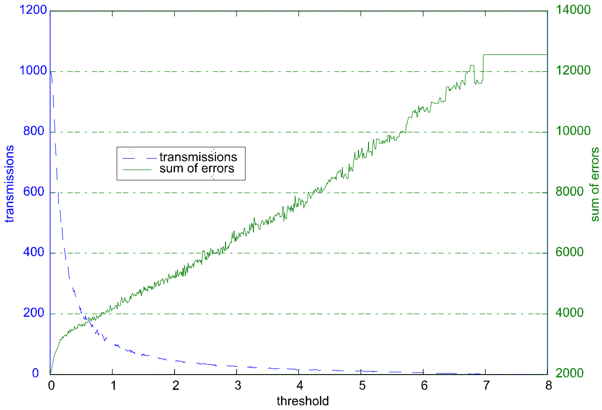

Fig. 5: Results for Gramian Data fusion.

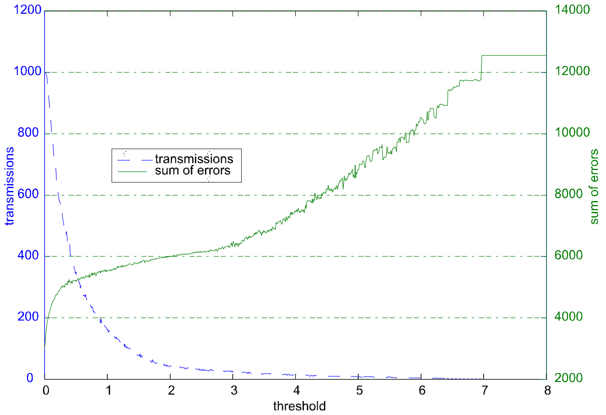

Fig. 6: Results for average data fusion.

Gramian data fusion. At 20% it is about 1.5 times higher. First, the influence of the threshold can be seen. Second, the effectiveness of the fusion method is obvious.

OUTLOOK

The ongoing work will use the properties of the Gramians to optimise the network topology by reducing it to a not fully-connected system. Next, the design of a controller, which was omitted here, will be analysed.

References:

[1] João P. Hespanha, Payam Naghshtabrizi, and Yonggang Xu. Networked Control Systems: Analysis and design, 2006. “To appear in the *Proc. of IEEE*, Special Issue on Networked Control Systems”.

[2] Muis A. Montestruque and Panos J. Antsaklis. On the model-based control of networked systems. *Automatica*, 39(10):1837—1843, October 2003.

[3] Reza Olfati-Saber. Distributed kalman filter with embedded consensus filters. In *Proc. of the 44th IEEE Conference on Decision and Control, and the European Control Conference 2005*, pages 8179—8184, Seville, Spain, December 2005. IEEE.

[4] Sokwhoo Rhee, Deva Seetharam, and Sheng Liu. Techniques for minmizing power consumption in low data-rate wireless sensor networks. In *2004 IEEE Wireless Communications and Networking Conference*, volume 3, pages 1727—1731, Piscataway, NJ, USA, 2004. IEEE.

[5] Andrew Stubbs and Geir E. Dullerud. Networked control of distributed systems: A testbed. In *Proc. of IMECE 200*, pages 1—5, New York, New York, November 2001. 2001 ASME International Mechanical Engineering Congress & Exposition.

[6] Yodyium Tipsuwan and Mo-Yuen Chow. Control methodologies in networked control systems. *Control Engineering Practice*, 11:1099—1111, October 2003

[7] Yonggang Xu and João P. Hespanha. Estimation under uncontrolled and controlled communications in networked control systems. In *Proceedings of the 44th IEEE Conference on Decision and Control and the European Control Conference 2005*, pages 842—847, Seville, Spain, December 2005. IEEE

[8] Greg Welch and Gary Bishop. An introduction to the Kalman filter. http://www.cs.unc.edu/~welch/kalman/, 2001, ACM SIGGRAPH 2001

[9] Arthur Conley and Mario E. Salgado. Gramian based interaction measure. In *Proceedings of the 39th IEEE Conference on Decision and Control*, Sydney, Australia, December 2000. IEEE

Authors:

Dipl.-Ing. Peter Hilgers
University of Freiburg – IMTEK
Department of Microsystems Engineering
Georges-Köhler-Allee 078
79110 Freiburg
Phone: +49 761 2037305
Fax: +49 761 2037439
E-mail: Peter.Hilgers@imtek.de

Prof. Dr.-Ing. Christoph Ament
TU Ilmenau
Institute for Automation and Systems Engineering
PF 100565
98684 Ilmenau
Phone: +49 3677 692814
Fax: +49 3677 691434
E-mail: Christoph.Ament@TU-Ilmenau.de