MŰEGYETEM 1782

BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS
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Resonator-based signal processing in sensor networks

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PhD Thesis booklet
2012

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2012

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1 Introduction and Research Goals

The design and analysis of distributed systems is an emerging research area. Following the new trends of technology, the distributed architecture has already appeared in real-time signal processing systems as well. In these systems, the signal sensing and processing are realized on spatially separated devices which are interconnected over a multiple access communication channel. The advantages of this architecture over the direct, wired connection of each device are [Zamp08]:

- flexible arrangement,
- easy installation,
- scalability.

The aim of the thesis is the investigation of closed-loop signal processing systems, where the feedback signals are transmitted over a wireless communication link. In this context, the so-called resonator based signal processing structures are investigated which offer an efficient framework for processing periodic signals [Pec86]. The emphasis is put on the application of resonator based structures with dynamic feedback which are special control loops developed for eliminating periodic disturbing signals [Sujb97].

The investigation of real-time systems containing networked communication in the feedback path was motivated by the development of an experimental active noise control (ANC) system where the noise sensing is performed by wireless sensors. The wireless data transfer offers high flexibility, but the uncertainties of communication raise several technical and scientific questions to be answered.

The goal in active noise control is the suppression of acoustic noises by means of destructive interference. Acoustic noises often contain periodic components, hence the deployment of resonator based structures is reasonable [Sujb97]. Since the noise sensing microphones are spatially distributed, the wireless data transmission enables the reduction of the physical complexity of the system by eliminating the wires. WSNs are dedicated platforms for wireless signal sensing, so they offer a promising technology for the realization of spatially distributed systems. The requirements posed by ANC systems and resources offered by WSNs determined the research goals essentially; nevertheless, most of my results are not confined to WSNs, but are generally true for any networked communication.

Resonator-based structures are similar to the LMS-based (Least Mean Square) algorithms. Both of them are signal-model-based structures, which means that a so-called conceptual signal model is constructed according to the nature of the signal to be processed, and the structure of the signal processing algorithm is fitted to the signal model. Resonator based structures assume a periodic signal model [Pec86], while LMS-based methods assume general stochastic signals [Wid96]. The similarity allows us to extend some results from the resonator-based structures to LMS-based algorithms.

WSNs are promising platforms for the design of distributed systems due to the low cost commercial sensor nodes which can be deployed in various environments. WSNs are generally composed of several simple but intelligent devices that are able to monitor some physical phenomenon, and they communicate with each other over a multiple access communication medium [Bur09]. The sensor nodes generally communicate over a radio channel. The intelligent sensor nodes are able to operate autonomously, and they can also perform simple arithmetic and logical operations.

The basic concepts of WSNs are the economical manufacturing, maintenance and energy consumption, hence the resources of sensor nodes of the network are limited. Due to the limited resources, WSNs cannot be regarded as ideal data acquisition systems, which should be taken into account in such applications where the quality of data acquisition is crucial. The signal sensing and transmission are especially important in real-time systems, where the uncertainties in the signal path may have serious effects on the whole system. The real-time requirements of the closed-loop signal processing systems and the limited resources of the sensor nodes do not allow to take the advantage of all the benefits offered by WSNs (e.g., establishment of large scale ad-hoc networks); however, the deployment of WSNs in real-time systems has a promising perspective due to their flexibility.

When WSNs constitute the integral part of the feedback path of a system, they essentially influence the operation of the whole system, and several problems arise [Math05, Zamp08]:

- distributed signal sensing and processing,
- limited communication bandwidth,
- data loss.

My thesis is organized according to these major issues. I investigate the effect of networked communication on the signal processing algorithms, and I also propose solutions to the different problems. Although the aforementioned problems emerge in the case of any networked communication, they especially dominate in WSNs.

Recently, the investigation of so-called Networked Controlled Systems (NCS) is an active research area, this thesis is a contribution to the results in this field.

2 Research Methods

My research activity can be structured as follows:

- Collecting practical experience during the realization of a test system.
- Development of new theoretical results:
  - Investigation of the effect of networked communication on the behavior of existing algorithms.
  - Design of new algorithms which fit the nature of networked communication.

2.1 Practical Methods of Research

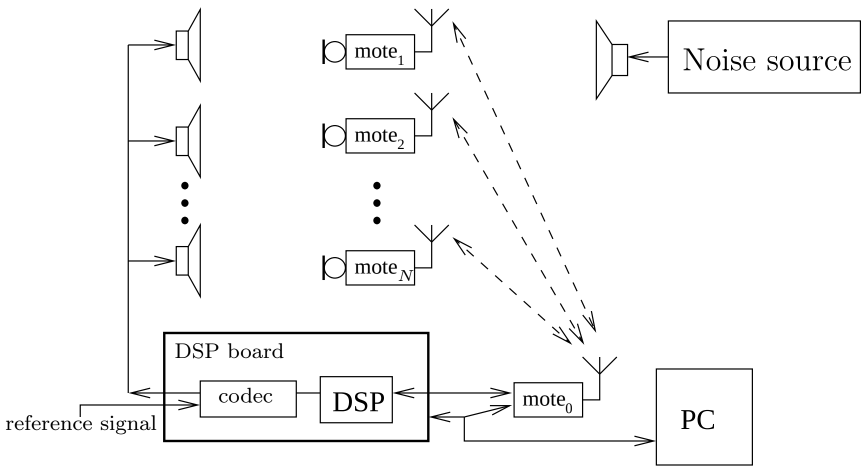

Figure 1: Testbed for wireless signal processing systems.

The investigation of practical problems in a wireless real-time system was performed during the design and test of an experimental wireless active noise control system depicted in Fig. 1. In this system, wireless sensors (mote$_1$ . . . mote$_N$) perform the sensing of the noise to be suppressed. The WSN is connected to a high performance digital signal processing (DSP) board which collects the data arrived from the sensors, and calculates the so-called anti-noise so that the noise power is minimized at the microphones' positions. The anti-noise is radiated by loudspeakers. The sensors and the DSP are connected through a gateway node (mote$_0$).

An ANC system can be regarded as a control system, where the goal is to achieve zero error, i.e., zero residual noise. The system to be controlled is an acoustic system. The feedback path contains the acoustic system extended with signal conditioner and converter circuits. The sensors directly observe the error signal that is the superposition of the noise and the anti-noise at the position of microphones.

During the design and implementation of the system, I have explored the communication and computational capacity as well as the limitations of wireless sensor nodes. This practical experience allowed me to formulate the research directions and the goals of the theoretical work.

2.2 Theoretical Methods of the Research

Research results involving networked closed-loop systems focus on two primary areas [Plo04]:

1) Design and analysis of algorithms taking into account the impact of networked communication (network-aware control).

2) Development of protocols for networked communications (control-aware network).

These two different approaches aim at simultaneously optimizing the two critical points of the system taking into account both the performance of the network and the requirements of algorithms. Most of the results of the thesis belong to the first category, i.e., the problems emerging due to the networked communication have been analyzed and solved by means of the tools of signal processing.

The results of the thesis are organized into the following three categories:

Signal sensing and transmission. Sensing and transmission of the signal is the first layer of the signal processing chain, so it plays crucial role during the system design. The delay caused by the distributed signal sensing and processing may cause serious problems, it can lead even to the instability of the whole system.

The effect of the delay induced by the distributed architecture is investigated using the stability conditions of resonator-based structures deduced by Sujbert [Sujb97]. These conditions allow us to calculate the maximal tolerable variation in the delay between the scheduled instants of the signal sensing and processing which still guarantees the stability.

The stability problem caused by the changing delay is resolved by the synchronization of the sensors and the central signal processing unit. After considering the possible alternatives, I have proposed a two-level synchronization mechanism assuming the architecture shown in Fig. 1: the first level of synchronization is performed between the sensors and the gateway, while the second level is performed between the gateway and the central processing unit.

The synchronization of two kinds of systems is considered in the thesis. The first one has a traditional architecture, where sensors transmit the raw samples of the observed phenomenon. The second system has a distributed computing architecture, where the intelligent sensor nodes perform the preprocessing of the signal using a resonator-based observer, and they transmit only the Fourier-coefficients of the observed signal. The local preprocessing of the signals enables data reduction, and increases the robustness of the system, e.g., against data loss.

The correct operation of the synchronization algorithms were also tested with practical experiences using the testbed in Fig. 1.

Communication with bandwidth constraints. In real-time systems, a hard deadline is specified for the transmission time for all of the data collected by the sensors, so the bandwidth limit of the communication channel can be the bottleneck of the whole system [Bai07]. The bandwidth of a communication link is highly determined by standards, costs and the power consumption, so the bandwidth constraints are often alleviated by using the computational capacity of the sensor nodes. The intelligent sensors are able to achieve data reduction by preprocessing the signal.

To achieve data reduction in a simple way, I have proposed the deployment of signed-error principle. This method can be applied in both resonator-based structures with dynamic feedback and also in the case of the FxLMS algorithm. The signed-error principle has been developed to reduce the computational complexity of adaptive filters [Ger84], however, its application in signal processing structures with dynamic feedback has not been known yet. The principle is simple: the sensor transmits only the sign of the observed error signal, which means even 50% reduction in the communication bandwidth requirement under realistic assumptions, taking into account the communication overheads as well.

The analysis of the algorithms introduced in the thesis is based on the well-known technics applied in the analysis of signed-error algorithms [Ger84], but I have extended them to signal processing structures with dynamic feedback. One of the characteristic features of signed-error algorithms is that they cannot achieve zero error even in noiseless case, and the speed of convergence is slow [Ger84]. The behavior of the algorithm is highly determined by the so-called convergence parameter, the value of which is chosen according to trade-offs between the steady-state error and settling time. To enhance the steady-state and transient performance, I have proposed a new algorithm which achieves generally faster convergence and smaller steady-state error by the adaptive tuning of the convergence parameter.

Data loss. Data loss cannot be avoided in real-time communication systems due to the finite deadline of data transmission and the inherently unreliable physical layer. The main contribution of the thesis relating to data loss is a set of conditions which enable us to predict whether the state variables of the resonator-based algorithms converge to their optimal values or not. The conditions can be evaluated using the pattern of data loss and the parameters of the algorithm.

The conditions are formulated first for the resonator-based observer assuming noiseless observations, then the results are generalized to a noisy case and resonator-based structures with dynamic feedback. In the noisy case, the convergence of the expected value of the state variables is investigated. This method is adopted from the adaptive filters' theory [Wid96]. In the analysis of systems with dynamic feedback, the so-called quasi-stationer approach has been used which is also a well-known technic in the field of adaptive filters. This method is valid with the assumption that the value of the convergence parameter is small [Wid96].

To deduce the necessary conditions of the convergence of the state variables, the observability condition of linear systems has been used. In the case of the so-called deadbeat observer, the condition of the convergence has been traced back to the convergence of the observer without data loss using the special properties of the state transition matrices introduced in [Pec86].

The sufficient conditions of the convergence of the state variables were deduced using the properties of the convergence of matrix series [Rozsa91].

3 Original Contributions

Statement 1.
I have proposed synchronization algorithms for signal sensing and processing in resonator-based signal processing systems, where the feedback is realized over a sensor network. The algorithms ensure the stability of the closed-loop systems. I have implemented the algorithms in an experimental system, and I have verified the proper operation of the synchronization algorithms in practice as well.

1.1. I have proposed a synchronization mechanism for a system where the sensors transmit the raw samples of the observed signal to the central processing unit. I have calculated the maximal tolerable variation in the delay between the sampling and signal processing instants which guarantees the stability of the resonator-based structure with dynamic feedback.

1.2. I have proposed a synchronization mechanism for the system where the sensors implement a local resonator-based observer, and they transmit the Fourier coefficients of the observed signal to the central processing unit. I have derived how long the resonator-based structure with dynamic feedback remains stable without synchronization.

Related publications: [1, 6]

Statement 2.
I have developed the signed-error resonator-based structure with dynamic feedback. The signed-error principle decreases the amount of data to be transmitted in the feedback path.

2.1. I have derived an upper bound on the mean-absolute error. The upper bound can be calculated according to the impulse response of the feedback path and the parameters of the algorithm.

2.2. I have proved that a tighter upper bound can be given on the mean-absolute error if the delay of the impulse response of the feedback path is known.

2.3. I have calculated a lower bound on the settling time of the feedback system.

2.4. I have developed a signed-error resonator based structure with improved convergence properties, and I have deduced a sufficient condition of the convergence of the algorithm. The convergence of the algorithm is sped up by the adaptive tuning of the convergence parameter.

Related publication: [7]

Statement 3.
I have developed the signed-error FxLMS algorithm. The signed-error principle decreases the amount of data to be transmitted in the feedback path.

3.1. I have derived an upper bound on the mean-absolute error. The upper bound can be calculated according to the impulse response of the feedback path and the parameters of the algorithm.

3.2. I have proved that a tighter upper bound can be given on the mean-absolute error if the delay of the impulse response of the feedback path is known. The statement has been proved with the following conditions: the reference signal has Gaussian distribution, and the part of the impulse response which does not include any delay has a monotonically decreasing absolute value.

3.3. I have calculated a lower bound on the settling time of the feedback system.

3.4. I have developed a signed-error FxLMS algorithm with improved convergence properties, and I have deduced a sufficient condition of the convergence of the algorithm. The convergence of the algorithm is sped up by the adaptive tuning of the convergence parameter.

Related publication: [2]

Statement 4.
I have given a necessary and a set of sufficient conditions for the convergence of the resonator-based algorithms if the signal stream to be processed contains missing samples. Convergence means that the state variables of the algorithm tend to their optimal values as time approaches infinity. The conditions can be evaluated using the pattern of data loss and the parameters of the algorithm.

4.1. I have given a necessary condition for the convergence of the observer.

4.2. I have proved that the necessary condition is also sufficient in the case of uniform resonator arrangement and deadbeat settling.

4.3. I have given a set of sufficient conditions for the convergence of the observer for the case when the state transition matrix of the observer has eigenvalues only with single multiplicity.

4.4. I have extended statements 4.1. and 4.3. to resonator-based structures with dynamic feedback. The extension of statement 4.3. was proved for the small value of the convergence parameter.

Related publication: [3]

4 Applications of the Results

The results can be used for the design and analysis of systems where the goal is the elimination of periodic disturbances, and the observations about the disturbing signal(s) are transmitted over a multiple access communication network. The signed-error principle proposed for data reduction can also be used even in the case of stochastic disturbing signals.

The proposed synchronization algorithms are applicable not only in closed-loop systems, but in every real-time measurement system where the synchronous sampling and processing of a signal is required.

The conditions for the convergence of resonator-based algorithms in the presence of data loss can also be applied during the design and analysis of measurement systems, where a real-time Fourier analysis is required, and the data stream may contain missing samples. The necessary condition of convergence helps to recognize the situations when the error-free estimation of the harmonic components is not possible. The sufficient conditions of convergence give safe regions of data loss parameters (e.g., data loss ratio) where the unbiased harmonic estimation can always be ensured.

The testbed developed to gain practical experience in the field of wireless closed-loop systems has already been applied with success in education to illustrate some of the specialties of distributed systems.

Publications Related to the Ph.D. Thesis

International Journal Papers

[1] Gy. Orosz, L. Sujbert, G. Péceli, "Synchronization and sampling in wireless adaptive signal processing systems," *Periodica Polytechnica-Electrical Engineering*, vol. 54, no. 1-2, pp. 59–70, 2010.

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Hungarian Conference Papers

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