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Active noise control over adaptive distributed networks

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ABSTRACT

This paper presents the implementation of Active Noise Control (ANC) systems over a network of distributed acoustic nodes. For this purpose we define a general acoustic node consisting of one or several microphones and one or several loudspeakers together with a unique processor with communication capabilities. ANC systems can use a wide range of adaptive algorithms, but we have considered specifically the Multiple Error Filtered-x Least Mean Square (MEFxLMS), which has been proved to perform very well for ANC systems with multiple microphones and loudspeakers, and centralized processing. We present a new formulation to introduce the distributed version of the MEFxLMS together with an incremental collaborative strategy in the network. We demonstrate that the distributed MEFxLMS exhibits the same performance as the centralized one when there are no communication constraints in the network. Then, we re-formulate the distributed MEFxLMS to include parameters related to its implementation on an acoustic sensor network: latency of the network, computational capacity of the nodes, and trustworthiness of the signals measured at each node. Simulation results in realistic scenarios show the ability of the proposed distributed algorithms to achieve good performance when proper values of these parameters are chosen.

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1. Introduction

It has been more than a decade since the wireless sensor networks (WSNs) were considered as a cheap, flexible and efficient solution for environmental and habitat monitoring, as well as for monitoring and maintenance of industrial equipment [1–3]. From the very first moment different acoustic applications were proposed [4,5], which paved the way for the specific wireless acoustic sensor networks (WASNs) whose sensor devices are microphones. These microphones are usually connected to a processor with some kind of communication and computation capability [6]. Applications that make use of this kind of acoustic nodes are numerous, see [7] and references therein, but they focus on the estimation of a common signal or parameter that can be measured by all the nodes [8], or on the estimation of node-specific signals sharing some common properties or parameters [9,10]. Another typical feature of a node relates to its configuration: the acoustic node is usually composed of a microphone plus a processor, where the processing unit is dedicated to recording, control and transmission tasks, and can eventually perform some signal processing algorithms before the transmission. However, for applications involving sound control in general, and particularly for active noise control (ANC) systems, this typical node structure needs to be modified in two aspects. First, the node should have the capacity of acting on the environment to control the sound rendering, that is, the node should be able to emit sounds through a loudspeaker or actuator. Second, the network

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should focus not only on the estimation of a particular signal or some related parameter, but on the design of the signals that will feed the loudspeakers and will control the sound field. To our knowledge, no WASN has been proposed where nodes have the capacity to control and modify their own environment.

Therefore, we will consider a generic acoustic node as a node with a certain computation capability to process signals, that can communicate to other nodes to exchange local and network status information, and which is also able to act on its own environment. The node can record signals through one or more microphones (sensors) and can emit sound signals via one or more loudspeakers (actuators). Moreover, nodes should make use of the network topology to process their own signals in a proper way. Some common topologies are the total diffusion networks, where all nodes are interconnected with the rest of the nodes; the mesh networks, where each node can communicate with a certain set of nodes; the tree networks, where communication between nodes is hierarchical; and the ring networks, where communication between nodes follows an incremental ordering along the network [11].

The specific application described in this paper is an active noise canceller or active noise control (ANC) system [12]. ANC systems try to reduce some unwanted noise by the addition of one or several secondary sounds specifically designed to cancel the first. In particular the system is intended to reduce the unwanted, also called primary, noise at the microphones' location. Fig. 1 shows an ANC system with K microphones and J loudspeakers. The signals recorded at the microphones are called *error signals* and denoted $e_k(n)$, the loudspeakers, called *secondary sources*, emit the filter output signals $y_j(n)$, and the acoustic channel impulse response between loudspeaker j and microphone k is modelled as a FIR filter. The unwanted noise is not depicted in Fig. 1, but the *reference signals* $x_i(n)$ entering the *multichannel adaptive controller* are correlated with it, and they will be used by the adaptive controller to appropriately design the output signals $y_j(n)$.

The algorithmic approach proposed in this paper is based on well known multichannel adaptive filters originally stated for a centralized system [12,13], where all signals $e_k(n)$ and $x_i(n)$ are available at the multichannel controller. Particularly, we have implemented the Multiple Error Filtered-x Least Mean Square (MEFxLMS) algorithm [14] over a distributed network, which in turn is based on the commonly used Least Mean Square (LMS) algorithm [15]. Regarding previous works on the implementation of the LMS algorithm on distributed systems, the first thorough studies were presented in [8,16], where distributed LMS is used on networks connected by incremental and diffusion strategies respectively. The authors show that the distributed LMS approach achieves good performance allied with low communication and computational requirements for linear estimation tasks. Although the algorithm proposed herein is based on distributed LMS-type algorithms [8,17], it has been extended to consider that our acoustic nodes do not only sense the environment but also modify it through its own actuators.

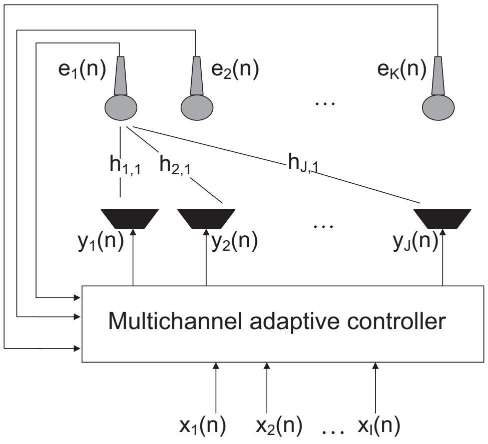

Fig. 1. Multichannel active noise controller with K microphones and J loudspeakers.

In the particular case of sound control systems, a distributed ANC system was first introduced in [18]. This system, called decentralized since their processors did not collaborate or interchange any local information, was based on a filtered-x scheme of the LMS algorithm [19]. Its main advantage is the scalability and the ability of distributing the computational burden, but it cannot overcome the centralized system performance except for uncoupled actuators and microphones. A similar decentralized ANC system is considered in [20] using adaptive non-linear filters. In both decentralized systems [18,20], each error signal $e_k(n)$ is only used by the corresponding processor, whereas reference signal $x(n)$ is common to all of them. For the herein proposed network of acoustic nodes, we consider that a common reference signal is available.

Consequently, the cooperation provided by a WASN would help ANC systems to achieve similar performance to centralized solutions, whereas they would also benefit from the advantages of distributed systems as scalability and low computational cost. The main contributions of the work herein presented can be summarized as:

- The MEFxLMS algorithm is formulated for WASNs as the distributed MEFxLMS (DMEFxLMS) where the calculation of the adaptive filters is carried out in a distributed way over a ring topology with incremental communication [8]. The computational burden is then shared among all the processors.
- We have extended the DMEFxLMS to a network whose communication is affected by a constant latency. To deal with this latency, the DMEFxLMS has been reformulated introducing two new parameters: the first one acts in the meantime between two network information arrivals, deciding if the node adapts itself based on its local measurement or waits for the new network information. The second parameter only acts when the network information arrives at each node, providing different combinations of both network and local information.
- We have carried out a set of simulations using real acoustic channel responses in order to evaluate the influence of the new parameters on the ANC system performance. We propose proper values of both parameters depending on the network latency, the node

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