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Pulse-coupled time synchronization for distributed acoustic event detection using wireless sensor networks

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ABSTRACT

Time synchronization has proven to be critical in sensor fusion applications where the time of arrival is utilized as a decision variable. Herein, the application of pulse-coupled synchronization to an acoustic event detection system based on a wireless sensor network is presented. The aim of the system is to locate the source of acoustic events utilizing time of arrival measurements for different formations of the sensor network. A distributed localization algorithm is introduced that solves the problem locally using only a subset of the time of arrival measurements and then fuses the local guesses using averaging consensus techniques. It is shown that the pulse-coupled strategy provides the system with the proper level of synchronization needed to enable accurate localization, even when there exists drift between the internal clocks and the formation is not perfectly maintained. Moreover, the distributed nature of pulse-coupled synchronization allows coordinated synchronization and distributed localization over an infrastructure-free ad-hoc network.

1. Introduction

Localization systems based on fusing information from a collection of sensors have captured the attention of researchers due to their simple yet powerful operating principles. In sensor fusion localization algorithms, the first element is the data association, where precise timestamps are required to ensure accurate localization. This poses the challenge of having an accurate common time notion among sensors. The concept of precision, however, is application-dependent and can vary from less than a microsecond up to seconds. Recently, several synchronization algorithms for sensor networks have been designed to provide a general framework for synchronization. Packet-based synchronization strategies such as RBS (Reference-Broadcast Synchronization) (Elson, Girod, & Estrin, 2002), TPSN (Timing-sync Protocol for Sensor Networks) (Ganeriwal, Kumar, & Srivastava, 2003), FTSP (Flooding Time Synchronization Protocol) (Maróti, Kusy, Simon, & Lédeczi, 2004), GTSP (Gradient Time Synchronization Protocol) (Sommer & Wattenhofer, 2009), PulseSync (Lenzen, Sommer, & Wattenhofer, 2009), and Glossy (Ferrari, Zimmerling, Thiele, & Saukh, 2011), have been recognized as powerful alternatives for performing periodic time synchronization in sensor networks and currently comprise the state-of-the-art standards. An appealing alternative approach to periodic time synchronization is *post facto* synchronization (Sallai, Kusý, Lédeczi, & Dutta, 2006), in which the network synchronizes after a significant event has occurred thus reducing the network traffic needed in traditional periodic synchronization strategies. However, *post facto* synchronization requires either the existence of a third party leader node, or the existence and maintaining of a skew table and a routing protocol (Sallai et al., 2006). These extra requirements on both the network and the processing capabilities of the sensor nodes make the scalability of *post facto* synchronization difficult in an unreliable network of low capability nodes. Lately, the bio-inspired paradigm of pulse-coupled oscillators (PCOs) (Mirollo & Strogatz, 1990; Peskin, 1975; Werner-Allen, Tewari, Patel, Welsh, & Nagpal, 2005) has received increased attention in the communications community due to its inherent scalability and simplicity (Hong & Scaglione, 2005; Hu & Servetto, 2006), emerging as a new alternative to traditional packet-based strategies.

In pulse-coupled synchronization, each participating node keeps

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track of a periodic phase variable. Whenever this phase variable reaches a threshold value, the node broadcasts an impulse-like signal. The rest of the time the node is sensing the channel for firing signals from other nodes. When a firing signal is sensed, the node shifts its phase variable according to a function known as a phase response function (Canavier & Achuthan, 2010; Daan & Pittendrigh, 1976), whose shape determines the stability properties of the synchronization algorithm (Mauroy, 2011; Wang & Doyle, 2012; Wang, Núñez, & Doyle, 2012a). Although pulse-coupled synchronization was first introduced concurrently with packet-based strategies, only recently has its applicability been explored in detail, since the packet-exchanging nature of communication networks facilitates the application of packet-based synchronization protocols. Nonetheless, the progress in radio technology and network standards has made pulse-coupled synchronization feasible to implement using ultra-wide bandwidth pulses, or preambles in an IEEE 802.11 network (Wang, Núñez, & Doyle, 2012b). Moreover, by transmitting simple identical pulses instead of full length packet messages, the pulse-based synchronization strategy eliminates the imprecision due to high stack layer delays, protocol processing, or software implementation arising in traditional packet-based synchronization strategies. In addition, pulse-coupled synchronization considers each received pulse identically, since exchanged pulses are independent of their origin (Hong & Scaglione, 2005; Pagliari & Scaglione, 2011), and is inherently a distributed strategy that does not require the selection of a root, or leader, node to flood the network with its local time. In pulse-coupled synchronization, the common time of the network is agreed by all the participating nodes via simple local interactions, which makes synchronization robust to disconnections of any node. Although early implementations of pulse-coupled synchronization showed an inferior performance with respect to classical approaches as FTSP, as reported in Werner-Allen et al. (2005), a deeper understanding of the pulse-coupled principle has allowed researchers to optimize the strategy (Wang & Doyle, 2012; Wang et al., 2012a). Recently, the optimized pulse-coupled synchronization strategy has been shown to have comparable accuracy to the state-of-the-art packet-based synchronization strategies, while reducing energy consumption by using a refractory period to reduce idle listening (Wang et al., 2012b). Moreover, an implementation in programmable FPGA-based radio boards (Brandner, Schilcher, & Bettstetter, 2016), using a single-carrier physical layer with 5 MHz bandwidth and quadrature phase-shift keying modulation, has shown precisions in the low microsecond range, which outperforms early hardware implementations of FTSP (see Maróti et al., 2004). Despite the recent re-emergence of pulse-coupled synchronization, which has motivated both analytical- (Wang & Doyle, 2012; Wang et al., 2012a; Núñez, Wang, Teel, & Doyle III, 2012, 2015a, 2015b) and general testbed-based (Brandner et al., 2016; Hong & Scaglione, 2005; Pagliari & Scaglione, 2011; Tyrrell et al., 2010) studies, an application of this technique to a practical functional system has not been reported yet.

The present paper studies the application of pulse-coupled synchronization to an acoustic event detection system designed to locate the source of an acoustic event in a two-dimensional space, by using an acoustic-capable wireless sensor network. The particular acoustic event detection system of interest is inspired by military applications on locating sources of gunfire or explosions by soldier worn acoustic sensors (Cakiades, Desai, Deligeorges, Buckland, & George, 2012; George & Kaplan, 2011; Sallai, Lédeczi, & Völgyesi, 2011; Volgyesi, Balogh, Nadas, Nash, & Ledeczi, 2007). Initially, solutions given by such systems were based on local measurements taken by an array of microphones, which allowed the system to locate the source based on angle-of-arrival (AoA) triangulations. The appearance of sensor networks enabled a networked solution where localization is carried out using sensor fusion techniques. However, this poses the extra requirement of having a common time reference. A variety of approaches to tackle both sensor fusion and time synchronization have been investigated. The system in Volgyesi et al. (2007) is formed by a network of multi-channel sensors able to gather time-of-arrival (ToA) as well as AoA measurements. Fusion is conducted by a central node and time synchronization is achieved by using the *post facto* strategy given in Sallai et al. (2006). A key assumption is that acoustic events are sporadic, and thus *post facto* synchronization allows resource savings by synchronizing the network only after an event has occurred, rather than keeping the network in sync all the time. Alternatively, the system presented in Sallai et al. (2011) uses single channel sensors that gather ToA measurements and fuses them in a central unit. It is assumed that each sensor is equipped with a GPS receiver and then precise time synchronization is available; the main drawback of this approach is that the GPS signal needs to be accessible at all times. In this work, localization is performed using ToA measurements from single channel sensors, while the time synchronization problem is solved using pulse-coupled synchronization. The particular acoustic event detection system under consideration is a patrolling squadron, i.e., sensors are free to move yet they try to maintain a given geometric formation at all times. The system is able to implement a variety of formations and it performs localization using sensor fusion algorithms based on ToA measurements. Two approaches are proposed to solve the localization problem, a standard centralized estimator that fuses ToA measurements from all sensors at a central node, and a distributed approach where each sensor in the network solves a reduced localization problem using only a subset of the ToA measurements, and then the estimations are fused by means of distributed average consensus algorithms. The distributed approach presented is in line with the general aim to construct a fully distributed system where both synchronization and localization are achieved by means of simple interactions between neighboring sensors. To enable communication in the network, for both synchronization and measurement sharing, a pure-broadcasting infrastructure-free ah-hoc network is proposed, for which pulse-coupled time synchronization is the natural choice. The effectiveness of the system is tested by simulating the different formations in QualNet$^{\mathrm{TM}}$, a widely used commercial network simulation tool. Preliminary results of this study were presented in Núñez, Wang, Desai, Cakiades, and Doyle III (2012).

The contributions of this manuscript are twofold. First, the application of pulse-coupled synchronization to a practical distributed system is shown, putting special attention to the feasibility of the implementation and the level of accuracy achieved, which is shown to be sufficient for the particular system under study. Secondly, a fully distributed localization strategy is proposed, which allows network-wide localization on a sparsely connected sensor network.

1.1. Notation and basic definitions

In this work, $\mathbb{R}$ denotes the real numbers, $\mathbb{R}_{\geq 0}$ the set of nonnegative real numbers, $\mathbb{Z}_{\geq 0}$ the set of nonnegative integers, $\mathbb{R}^n$ the Euclidean space of dimension n, and $\mathbb{R}^{n\times n}$ the set of $n \times n$ square matrices with real coefficients. $\mathbf{I}_n$ denotes the n by n identity matrix, for a vector $\mathbf{v} \in \mathbb{R}^n$, $\mathbf{diag}(v)$ denotes the diagonal matrix with the elements of $\mathbf{v}$ in the diagonal. We denote $\mathbf{1}$ as the vector of all ones of appropriate dimension. For a countable set χ, $|\chi|$ denotes its cardinality. For two sets Λ_1 and Λ_2, $\Lambda_1 \setminus \Lambda_2$ denotes their difference.

1.2. Sensor network and formations

The acoustic event detection system is comprised of N identical independent agents, distributed according to a given configuration, equipped with an acoustic sensor (microphone), a central processing unit, and a wireless transceiver in charge of establishing communication between sensors. For simplicity, we consider that the agents live in a two-dimensional Euclidean space, i.e., $\mathbb{R}^2$. The agents act as a patrolling squadron, meaning that they are free to move yet they try to maintain a geometric formation at all times, for security, tactical,