Pervasive and Mobile Computing 44 (2018) 1–30

Contents lists available at ScienceDirect

Pervasive and Mobile Computing

journal homepage: www.elsevier.com/locate/pmc

Swarm-Sync: A distributed global time synchronization framework for swarm robotic systems

Meetha V. Shenoy *, Anupama K.R.

Department of Electrical & Electronics Engineering, BITS Pilani, K.K. Birla Goa Campus, Zuarinagar, Goa, 403726, India

ARTICLE INFO

Article history:
Received 19 July 2017
Received in revised form 7 January 2018
Accepted 9 January 2018
Available online 6 February 2018

Keywords:
Time synchronization
Mobile wireless sensor network
Swarm robotics
Relative skew fingerprinting

ABSTRACT

Time synchronization is a crucial service task in a distributed network. Although several works are reported in routing and medium access control of mobile wireless sensor networks (MWSNs), or for navigation in a collaborative swarm of robots, prior time synchronization is stated as one of the prior requirement. In this paper, we study the problem of time synchronization over a wireless network for a swarm robotic system. We propose a fully decentralized, energy efficient framework for global synchronization of swarm of robots. The major contribution of this work is in terms of proposing a scalable, topology independent, mobility-assisted time synchronization framework with resynchronization interval in the order of several minutes (tested up to 10 min) which we believe will accelerate development of swarm robotic systems and mobile wireless sensor networks for several human-friendly real-world applications. The proposed framework which implements time synchronization in two phases, (1) One-way time offset compensation and (2) Relative skew fingerprinting based frequency offset compensation, is flexible and can be tuned easily to suit several application scenarios. Another unique characteristic of the framework is that it utilizes only one-way messages for the time offset and frequency offset compensation. We also demonstrate that the protocol scales very well for multi-hop scenarios and that bounded synchronization error across the network can be achieved using the framework. Analysis on the suitability of our framework for dynamic environments is also presented. We also present a fair comparative analysis of our work with the predictive protocols based on techniques such as Linear regression, Linear prediction and Kalman filter and consensus based synchronization proposed for static networks. The results and analysis presented here are derived from the analytical and empirical study on mobile nodes/robots spread over a duration of 5 months.

1. Introduction

Swarm robotics is a nascent branch of research which integrates the potential advantages of distributed computing such as fault tolerance and scalability into the field of robotics. Swarm robotic systems incorporate decentralized, cooperative, self-organized, simpler robots which utilize local interactions among each other to produce complex and emergent behaviors which are beyond the capabilities of individual robots [1]. Swarm robots offer parallelism in their behavior whereby multiple, cooperating cost-effective robots can achieve a given task quicker than a single robot by dividing the task into sub-tasks and executing them parallelly. The concept of swarming is gaining interest among the scientific community and recently many applications have been proposed for utilizing swarm robots in a wide spectrum of applications such as military operations [2],

* Corresponding author.
E-mail addresses: meetha@goa.bits-pilani.ac.in (Meetha V. Shenoy), anupkr@goa.bits-pilani.ac.in (Anupama K.R.).

https://doi.org/10.1016/j.pmcj.2018.01.002
1574-1192/

search and rescue [3], precision agriculture [4], inventory management in a warehouse [5] etc. The major factors which desist swarming include, but are not limited to, lack of robust methods of swarm synchronization, energy efficient-distributed schemes for dynamic task allocation of robots, localization and communication mechanisms for achieving coordinated control of robots.

Interestingly, swarm robotic systems and Wireless Sensor Networks (WSNs) share several common characteristics such as use of a large number of robots/nodes, limited individual capabilities of robots/nodes, cooperative behavior etc. Both domains can operate complementary to each other such that the swarm robots can utilize wireless sensor network for communication and cooperative behavior, while WSNs can take advantage of the mobility provided by swarm robots to improve its sensing range, thereby forming a self-healing network. Static WSNs are successfully deployed in several applications such as precision agriculture [6], monitoring of oil and gas pipelines [7] etc. By combining the best of two domains swarm of robots can change the way we live today and can be utilized for several applications which mitigate human effort, provide a safe working environment or at times even save human lives.

Time synchronization is a critical system maintenance task in any distributed system, as information collected over a distributed network has significance only when associated with a time stamp and location stamp. Real time wireless control, cooperative data collection and navigation, task allocation and task migration in a distributed swarm robotic network is possible only if the robots are synchronized to a common notion of time. Improving the resynchronization interval, accurate time synchronization under dynamic environmental conditions, limiting synchronization errors within a deterministic bound in multi-hop scenarios, etc. are open problems of research even for static WSNs. Time synchronization error can be within a few hundreds of milliseconds for most of the static WSN applications, whereas swarm robotic applications will require higher synchronization precision (lesser error bound, in the order of a few tenths or hundredths of microseconds) because mobile robots, in addition to monitoring or controlling the environment in which they are deployed, may utilize timing information for their localization, cooperative path planning, navigation, aggregation, dispersion, etc. Although several works are reported in the field of routing and medium access control for mobile wireless sensor networks, or for navigation in a collaborative swarm, prior time synchronization is stated as one of the assumptions when time dependency is involved [8–10]. Time synchronization is a pre-requisite for other layers of the protocol stack and thus most of the research in mobile wireless sensor networks (MWSNs) and swarm robotics is still limited to simulation based study. With the constraints such as limited communication bandwidth, limited battery power and limited processing power, time synchronization for a dynamic network such as swarm robotic system is a challenging problem to solve.

In this paper, we address the problem of time synchronization for swarm robotic systems, which makes use of a wireless network for communication among members of the swarm. We propose a novel, energy efficient, global time synchronization framework suited for a dynamic network such as a swarm robotic system. The proposed time synchronization framework is topology independent and can provide a bounded global synchronization error across the network. Another noteworthy feature of the framework is the improvement of resynchronization interval to an order of several minutes, thus reducing the communication overhead. With this development, the authors believe that we are one step closer to utilizing swarm robots in several human-friendly applications such as precision agriculture, search and rescue, localization in indoor/outdoor environments, inventory management in a warehouse, etc. Rest of the paper is organized as follows. Section 2 provides a description of the important terms related to time synchronization referred in this paper. In Section 3, we present the problem formulation for Swarm-Sync framework. Section 4 presents a brief review of related works in literature. Section 5 presents an analysis of the sources of error in popular time synchronization techniques which utilize MAC level timestamping. Section 6 elaborates the proposed Swarm-Sync framework, its experimental analysis for single and multi-hop scenarios and its suitability for dynamic environmental conditions. This section also provides a brief overview of the robot designed and utilized by us for our experimental work. In Section 7, we provide a fair comparison of Swarm-Sync framework with the popular state-of-the-art time synchronization protocols proposed for WSNs.

2. Preliminaries

A node in a distributed network is usually clocked using a quartz crystal, excited by a clock driver embedded into the node hardware. The notion of time in a microcontroller based node can be maintained using a Real Time Clock (RTC) implemented in software or as a dedicated hardware/microcontroller peripheral. RTC can be maintained in software using a timer peripheral that generates an interrupt at a specified time interval. The number of interrupts are counted and then converted to time. In practice, RTC accuracy depends on the accuracy of the quartz crystal oscillator and the granularity of RTC determines the granularity of time synchronization. To elaborate the concept of time synchronization we define the following terms referred in this paper.

Instantaneous offset $\theta(t)$: The difference between the time reported by two nodes at a given instance is referred as time offset or instantaneous offset [11]. The nodes in a network are to be synchronized such that the instantaneous time offset among nodes are maintained within limits as demanded by the application. If the time reported by the reference node and a given node in the network is $R(t)$ and $N(t)$ respectively, then their instantaneous offset ($\theta_R^N(t)$) is given as

$$\theta_R^N(t) = R(t) - N(t) \tag{1}$$