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Wireless sensor network-based communication for cooperative simultaneous localization and mapping ☆

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ABSTRACT

This paper presents a novel approach of using a Wireless Sensor Network (WSN) as the communication means for Multi-Robot, Cooperative, Simultaneous Localization and Mapping (CSLAM) applications investigating the associated design challenges and suggesting corresponding solutions. Although the proposed approach brings several benefits including an increased coverage and communication range, self-organization capabilities, quick deployment, and flexible architecture, the realization is interrelated with performance in terms of energy efficiency and reliability. In this respect, the applicability of the WSNs for the presented approach is investigated. Centralized and distributed map merging methods in WSN-based CSLAM are evaluated in detail and the impacts of packet delays and losses on the performance of CSLAM algorithms are shown. Additionally, the involved network congestion and contention dynamics are presented, while the effects of observation range, speed, time intervals between observations, and odometry readings on the SLAM accuracy are shown based on an extensive set of simulation studies.

1. Introduction

Simultaneous Localization and Mapping (SLAM) is a process used by mobile robots to build a map of an unknown zone by using a sequence of measurements, while at the same time they keep track of their current locations [1]. Due to the measurement noise and motion noise, uncertainty is inherent in robotic mapping [1–3]. A team of multiple robots can map an unknown zone more quickly and robustly than a single robot. This process is known as Cooperative SLAM (CSLAM) [4]. SLAM algorithms rely on the environment representations, maps, which consist of a set of features detectable by the robot sensory system [3]. There are three well-known map representations in SLAM, namely the occupancy-grid maps, the topological maps, and the landmark-based maps. In the case of the occupancy-grid maps, the environment is represented in a discrete grid which is composed of cells. Each cell is assigned a value which represents the probability of occupancy. Grid resolution is the key variable of occupancy-grid maps [3]. As the grid resolution decreases, average CPU-time and memory requirement needed for global localization decreases but average localization error increases. The disadvantages of occupancy-grid maps are that they suffer from discretization errors and require a lot of memory resources. Topological maps

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consist of vertices and edges. A vertex represents a specific place and an edge indicates the traversability between two connected vertices. Landmark-based maps store landmarks' locations and robots' positions in state vectors. In a two-dimensional landmark-based map, the location of a landmark is stored in the Cartesian coordinate system. A covariance matrix associated with the map is used to describe the uncertainties of landmarks' locations and robots' positions [4]. The memory size required to store a landmark-based map is very small comparing to an occupancy-grid map or a 3D map.

This paper presents the design considerations of using a Wireless Sensor Network (WSN) as the communication means for CSLAM and investigates the potential advantages and design challenges. In CSLAM applications, robots come together at some predetermined locations to share their findings. This makes the operation slower. If communication is available all the time, then the operation may run faster. In this respect, the use of WSNs can improve communication between robots and a control center responsible for overall coordination for both centralized map merging and distributed map merging approaches, and can address the main problem of outdoor CSLAM applications, which is the lack of communication between the robots and the control center (or human operator on the semiautonomous mode).

Different from the traditional approaches that use IEEE 802.11b/g/n-based wireless networks to communicate between robots and a central agent, the efficient use of WSNs is proposed here for the distributed communication and coordination in CSLAM. According to this approach the wireless sensor nodes, beyond their main task of sensing the environment to collect information, provide a communication infrastructure to mobile robots. The proposed WSN-based CSLAM has a potential use for robotic exploration and SLAM applications especially in hazardous environments or situations like nuclear disaster zones, chemical attack zones, minefields, even conventional battlefields or natural disaster sites. It is important to note here that, in addition to adapting WSNs to the needs of CSLAM, the proposed SLAM strategy needs to be adapted to the features of the employed WSNs.

This paper extends the conference publication [5] of Tuna, Gulez and Gungor with more details about the proposed system, extensive new results and findings from a set of simulation studies on the performance of the centralized and distributed map merging methods in WSN-based CSLAM. Different from [5] which only address WSN communication performance in terms of both node level parameters and network level parameters for the proposed application, in this paper, the advantages of the proposed WSN-based CSLAM and the associated communication challenges are thoroughly investigated in order to focus on designing strategies to deal with the limitations of WSNs for CSLAM applications. In addition, the problem statement is described in more detail, while all pictures and result graphs have been updated to the new findings of the ongoing work. The main contributions of this paper can be summarized as follows:

- The key WSN design issues and challenges for CSLAM are revealed. In addition, the relationship between data transmission rate and lifetime of contemporary sensor network platforms, such as mica2, imote2, and Telos sensor motes is identified by simulation.
- Centralized and distributed map merging approaches in WSN-based CSLAM are evaluated, and the impacts of packet delays and losses on the performance of SLAM algorithms are shown. The dynamics of network congestion and contention in WSN-based CSLAM are investigated, and the effects of the observation range, the speed, the time interval between observations, and the time interval between odometry readings on the SLAM accuracy are shown based on an extensive set of simulation studies.
- The nonlinear relationship between the number of data transmissions in WSNs and battery voltage is demonstrated through empirical field measurements using Telos sensor network platforms in the field.

The remainder of the paper is organized as follows. A novel WSN-based communication for CSLAM is introduced in Section 2, while energy consumption issues for the proposed approach are investigated in Section 3. In Section 4, the design considerations of WSNs for CSLAM are studied in detail. In Section 5, centralized and distributed map merging methods in WSN-based CSLAM are examined. Finally, the paper is concluded in Section 6.

2. WSN-based communication for CSLAM

In CSLAM applications, robots meet at predetermined locations to share their findings, the map data. This necessity is due to the communication unavailability at some points and is the main limitation of all CSLAM applications. To address this limitation, in this study, we propose the use of WSNs to enable communication between robots.

Map merging is one of the most important steps of CSLAM applications. It is basically the process of building a consistent model of an unknown zone by using sensor data collected from different robots. In the centralized map merging approach, observations from all robots are used to build a map [6]. On the other hand, in the distributed approach, each robot independently builds the local sub-map of the zone around itself. Then, local sub-maps are fused into a global map periodically [4,7,8]. In the proposed approach, since the robots exchange map data through WSN communication channels, the performance of CSLAM map merging operation heavily depends on the performance of WSNs.

In general, WSNs offer many advantages like flexible installation and maintenance, fully mobile operation, and monitoring of environments inhospitable for humans, however they have some adverse properties due to the wireless channels used during transmission such as path loss, multi-path fading, and channel interference. Thus, WSNs are inherently, up to a certain degree, unreliable and unpredictable, which has been the case for many of the sensor network deployments [9,10]. However, recent work on radio diversity shows that WSN links can be nearly perfectly reliable with multiple radio bands [11]. A