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A Scalable Local Positioning System

Belal Al-Qudsi

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الحَمدُ لله

على تَيسير هذا ألبَحث. أودُ أن

أُهدي هذه الأُطروحة لأُمي و أبي و

زوجتي و أُختاي و إبني، تَقديراً لهم

على ما بَذلوهُ لأجلي و عَلى صَبرهم

طوال ألرحلة ألبَحثية.

Praise be to Allah

for facilitating this research.

I would like to dedicate this thesis to:

my mother, father, wife, sisters, and son for their support and patience throughout the journey of this research.

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Belal Al-Qudsi

Abstract

Indoor positioning is a service that is in high demand. Its goal is to locate a large number of users inside a building, and is widely known as local positioning system (LPS). It is particularly effective in large densely crowded places, such as hospitals, airports, parking areas, and on public transportation hubs. Furthermore, accurate indoor positioning is an essential technique in a so-called "smart factor". Several commercial radio frequency (RF) based systems achieve a high level of accuracy under outdoor conditions, however they fail when tested indoors.

Developing a single system that is suitable for a range of different conditions and purposes is a big challenge facing developers of LPSs. This research presents a multi-band scalable positioning system that not only provides accurate means of navigation, but also seamlessly expands the maximum number of reference and mobile nodes. Time synchronization is carried out wirelessly, minimizing the hardware required to set up the system easily.

Because of its high precision and immunity to RF interference, a multi-band frequency modulated continuous wave (FMCW) radar system has been designed to handle core time measurements. Several techniques and algorithms are specifically optimized to follow the special requirements of the FMCW radar system design. The system relies on commercial crystal oscillators (XOs) to generate its reference clock at each of its nodes. Due to the different manufacturing and temperature changes, each XO generates a slightly different frequency that has a great influence on the accuracy of the positioning estimate. A scalable FMCW based synchronization protocol is proposed to estimate the XO offset and compensate for it. The accuracy of the positioning system was enhanced by a factor of at least 3 in various conditions after compensating for the errors in measurements that are due to the frequency offset.

In order to withstand complex indoor conditions, a line-of-sight (LOS) searching protocol together with a particle filter (PF) tracking algorithm is considered. Measurements were carried out to evaluate the system in several practical conditions and to compare it with current state-of-the-art (SOA) techniques. The positioning outcomes were compared to a reference optical system with a precision of about 1 mm. The proposed system was evaluated with different configurations in two practical scenarios. The first experiment was performed outdoors in relaxed channel conditions, while a second indoor scenario was used to demonstrate the impact of the dual-band and the scalability of the system. The evaluation scenarios included areas with both LOS and non-line-of-sight (NLOS) conditions.

A root mean square (RMS) positioning error of less than 17 cm and 30 cm was achieved in a coverage area of around $500\,\mathrm{m}^2$, in both outdoor and indoor conditions respectively. The system was optimized for minimum positioning error with maximum effective coverage area. To the best of the author's knowledge, the proposed system outperforms the current commercial systems not only in the aspect of positioning error, but also in the coverage efficiency of the reference stations, which defines the minimum number of reference stations that are required to cover a specific area.

The thesis leads the reader from the system concept through the hardware realization, passing by the associated algorithms to the practical applications and challenges. The text also introduces its readers to the details of different practical system level techniques and emergent filtering algorithms that are especially optimized for the multi-band FMCW radar system.

Contents

1. Introduction

1.1. Motivation

Often we arrive at a huge facility and ask: Where are we? Where is the meeting room? How do we find the elevator? and so forth. It is always useful to be guided with landmarks and directions. In fact, knowing your position is a significant piece of information that may completely change critical decisions, not only for guidance purposes, but also for monitoring and controlling applications.
For a long time, humans have seeked different means by which to position themselves with respect to surrounding landmarks. An early step was the foundation of a so-called “astrolabe”, a historical tool that used the locations of the stars to provide a rough means of navigation. In spite of its moderate level of accuracy, people found plenty of applications for that tool. For example, it was particularly helpful when sailing and crossing deserts. Modern buildings contain complex instruments, sophisticated control systems, and a bundle of features to enhance the safety, comfort, and productivity of occupants. Many of these systems involve machine-to-machine wireless communication and require a certain level of connectivity between most of the equipment. Modern applications require accurate means of navigation to cope with the highly dense environment in which they are used. Accurate positioning plays a considerable role in evaluating the state of objects and connecting them with their surroundings to provide position related services. Yet the global positioning system (GPS) is available on almost every smartphone. With 28 operational satellites orbiting the earth, this system provides location information to any of its receiver units that has a good line-of-sight (LOS) with a set of its satellites. But if there are obstacles blocking its radio frequency (RF) signal, the GPS receiver often fails to operate. Conversely, positional information is most crucial in crowded and hidden areas where the connectivity to the GPS satellites is too low or even impossible. This is particularly true in large, crowded, and dense locations, such as hospitals, airports, parking areas, and public transportation hubs.
Accurate indoor positioning is a challenging task. Several commercial RF based systems achieve good accuracy in outdoor conditions. However, they fail when operating indoors. Due to the high complexity of the wireless indoor channel and RF interference from other wireless systems, commercial indoor positioning systems often fail to deliver the expected level of performance. While the range of applications for the positioning systems are diverse, commercial systems are

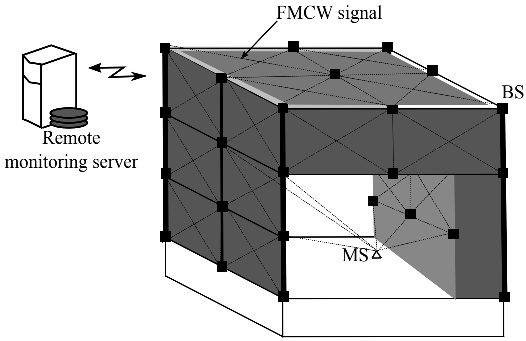

Figure 1.1.: Scalable positioning system concept

designed to fit specific applications.
A typical positioning system consists of many mobile stations (MSs) and an infrastructure of several base stations (BSs) deployed across a specific area in which the localization is carried out. As depicted in Fig. 1.1, a major concept of this research is to provide a scalable frequency modulated continuous wave (FMCW) radar based positioning system that can seamlessly extend to suit various indoor scenarios. Time synchronization is handled wirelessly, thus the system not only allows the maximum number of nodes to scale, but also delivers the required level of synchronization to perform accurate time measurements at many MSs. Moreover, to improve immunity against RF channel effects and interference, the radar front-end features multi-band functionality.
Along with the FMCW based time measurements, the system uses a particle filter (PF) tracking algorithm to fuse data from the multiple reference stations and frequency bands. Thus, the proposed local positioning system (LPS) ensures a flexible design that makes the most of the spatial and frequency diversities. Large parts of the front-end are integrated into an application-specific integrated circuit (ASIC) with a die size of only $2.4\,\text{mm}^2$.

1.2. Associated projects

The proposed system provides a flexible design that covers a wide range of applications. Indoor navigation is a particularly dominant form of use of the LPS. Another emerging application is structural health monitoring (SHM). This is essential for crucial security alarms in case of disasters such as earthquakes. Several nodes are deployed around a large structure as shown in Fig. 1.1. The nodes communicate with each other to detect movements in the structural elements

(a) Aircraft accident (b) Building collapse (c) Vessel fire

Figure 1.2.: ESPONDER project field tests

of a large building. Unlike in the case of indoor navigation, the SHM nodes are mostly stationary and may only move short distances over a long time period. The following European projects were addressed during the development of the LPS.

- **E-SPONDER:** A holistic approach towards the development of the first responder of the future. It is a European co-funded research and technology development project providing a suite of real-time data-centric technologies and applications, which provides actionable information and communication support to first responders acting during abnormal events (crises) that occur in critical infrastructure. The approach guiding the E-SPONDER project is based on the fusion of variable forms of field-derived data within a central system which will then provide information analysis and decision support applications at designated control centers locations in order to provide on site support to first responders that operate in critical infrastructure [1].
  The project is intended to support the first responder in crisis situations where the system needs to estimate the position for a mobile node using a range of information in an indoor scenario. As shown in Fig. 1.2, several practical scenarios where carried out to demonstrate the usage of the LPS to track the first responder in complex conditions such as: airplane crashes, collapsed buildings and incidents inside a vessel.
- **RECONASS:** Reconstruction and REcovery Planning: Rapid and Continuously Updated COnstruction Damage, and Related Needs ASSessment. This provides a monitoring system for constructed facilities, and gives a near real time, reliable, and continuously updated assessments of the structural condition of a building after a disaster, with enough details to be useful for early and full recovery planning. The above assessment should integrate seamlessly with automated, near real-time and continuously updated assessment of physical damage, loss of functionality, direct economic loss and needs of the monitored facilities [2]. As shown in Fig. 1.3, the final project demonstration was to

(a) Before detonation

(b) After detonation

Figure 1.3.: RECONASS project detonation experiment

monitor the structural elements of a building after an explosion event.

- **MAGELLAN:** A Multi-modal Authoring and Gaming Environment for Location based coLlaborative AdveNtures. The overall vision of MAGELLAN is to enhance game designer creativity by establishing a web platform for cost-effectively authoring, publishing, executing, and experiencing location based games. This unique integrated web-based infrastructure will be targeted at both skilled professional authors and everyday authors without in-depth technical skills. MAGELLAN will be underpinned by scientific research into the principles and technologies of creative and location-based experiences in order to ensure that the platform is innovative while also extending our broader scientific understanding of creativity. The main objectives of MAGELLAN are [3]:

  – To undertake foundational scientific research into the techniques of creativity for location-based games, from high-level concepts, to multimodal authoring, to the underlying technologies of location-based computing, so as to ensure the novelty and effectiveness of the platform.
  – To research and develop an innovative integrated and collaborative visual authoring environment dedicated to the creation and publication of new forms of multiplayer location-based games, and to validate this through trials involving a community of users across Europe.
  – To develop a scalable web platform featuring social networking and supporting the collaborative authoring, publication, browsing and execution of a large number of location-based games potentially involving multiple participants.

1.3. Literature review

With increasing demand for location-based services, accurate location estimation in indoor environments has been receiving considerable attention in industry and academia. Current positioning techniques can be placed into three main categories: approximate [4], finger-print based, and time-based positioning systems. The first technique estimates the position in an area near the reference sites. Although it is the simplest, its accuracy is limited. The second is finger-print based positioning. A positioning technique which relies on the received signal strength (RSS) is a typical technique that has already been addressed in a variety of literature for applying finger-printing based positioning [5]. Beside the high memory requirements of finger-printing techniques, the main disadvantage of this technique is its high sensitivity to changes in environment, therefore it only suits applications where the environment is relatively stable.

Time based techniques constitute another class of LPSs. In spite of being the most complex technique in terms of hardware requirements and processing, it is considered one of the most accurate positioning techniques. Time of arrival (TOA) and time difference of arrival (TDOA) are the most widely employed time based techniques. In this regard, ultrasound [6] and ultra-wideband (UWB) [7] systems have recently been receiving a lot of attention from researchers. This is due to their superior performance in resolving the LOS signal. Because of the very low signal propagation speed, the ultrasound LPS can reach a very high level of accuracy [6]. However, as a result of the signal's characteristics, the limited operating distance, as well as the signal's inability to penetrate obstacles, lots of practical demanding applications find this technique inappropriate. Instead, the UWB positioning systems have lower positioning error but much larger coverage and can penetrate many materials.

Modern UWB positioning solutions can theoretically reach sub-decimeter accuracy. However, indoor environments are usually challenging, as the probability of multipath propagation and non-line-of-sight (NLOS) conditions is often high. Having multiple reflections may dramatically degrade the accuracy of the position estimate and obscure the LOS signal.

An LPS may perform excellently in one scenario, while it may give a vastly inferior performance in another. A big challenge lies in the diversity and the instability of indoor environments. Lots of research can be found in the literature mitigating its effects on the final position estimate [8, 9]. It can be concluded that measurement diversity is a key concept that can boost the performance of the positioning system. Yet the term diversity is general; it can imply time, spatial, or frequency diversity.

Time diversity is simply achieved by repeating the underlying measurements. Although it is a simple approach, it reduces the update rate of the positioning system. Spatial diversity is a powerful approach, which is practically achieved by collecting measurements from different positions. One way to achieve spatial diversity is by simply expanding the number of reference stations. Industrial UWB positioning systems [7] have tight specifications to suit different scenarios and, naturally, occupy a wide frequency bandwidth. Thus, they lack the scalability required in terms of the maximum number of reference stations.

Aside from that, FMCW radar is vastly used in the literature and has recently been considered in emerging positioning systems [9, 10]. In contrast to the UWB technique, the FMCW does not instantaneously occupy a wide frequency bandwidth, rather the signal sweeps its frequency over time. Simultaneous signaling from multiple transmitters is possible with proper time guards among them. Furthermore, its hardware design allows for flexible signal characteristics and an easy design to integrate into a communication front-end. It is therefore well-suited to a scalable positioning system that is resilient to indoor RF channel changes, therefore it is used in this research as a time measurement technique.

In [9], a reconfigurable multiple input multiple output (MIMO) system for high-precision FMCW local positioning was suggested, in order to boost system performance by considering the angle of arrival (AOA) along with the time measurements as an additional measurement. Indeed, the technique does enhance the system performance in terms of mitigating the NLOS components and extending its maximum coverage area.

In [11], a robust dual-band LPS operating at the 2.4 GHz and 5.8 GHz industrial, scientific, and medical (ISM) bands was designed. It was concluded that the dual-band operation enhances the quality of radar measurements in both outdoor and indoor conditions. In [Pub1, Pub2], a modified dual-band system design was proposed and evaluated in both indoor and outdoor scenarios. It was concluded that the use of the FMCW technique, along with the dual-band capability, not only enhances the accuracy of the measurement, but also increases its coverage efficiency. This reduces the installation cost by requiring fewer reference nodes to cover the same area.

In [Pub3], an investigation into the feasibility of integrating an inertial measurement unit (IMU) with FMCW LPS to mitigate the effects of multipath was considered. It was concluded that the IMU sensor does enhance the accuracy of the positioning estimate but that it increases the complexity of the MS and requires tough processing.

In light of the standalone coverage of an efficient dual-band FMCW system, this research introduces a scalable LPS that is able to cope with complex channel challenges. Along with the FMCW based time measurements, the system uses a PF tracking algorithm to perform data fusion of the multiple reference stations and frequency bands. Thus, the proposed LPS ensures a flexible design that makes the most of the spatial and frequency diversities. In [Pub4], the standard deviation of the radar measurements was enhanced by a factor of two by compensating the crystal tolerance of the different radar stations.

1.4. Thesis statement

The goal of this work is to develop a positioning system which benefits from multiple data sources to provide a flexible design, that is able to scale in terms of the maximum number of reference nodes and provide a strong level of robustness against complex channel conditions.

1.5. Organization of the work

In order to fully grasp the dimensions of the work, this thesis covers both the hardware and algorithms behind the system along with the practical evaluation experiments. The second Chapter briefly reviews several general aspects in the field of positioning. The third Chapter is devoted to the principle of operation and the hardware details. Several techniques that are related to the theory of frequency modulated continuous wave (FMCW) radars are discussed and compared. A scalable mesh network synchronization protocol is discussed in Chapter 4. The relevant positioning and tracking algorithms are detailed in Chapter 5 and a discussion regarding practical outcomes is presented in Chapter 6 and Chapter 7. Finally, the outcomes are summarized and compared to state-of-the-art (SOA) positioning systems. An overview of the structure of the thesis is given in Fig. 1.4 by illustrating the fundamental components that are essential to perform the local positioning. Throughout the work, a BS is represented by a square shape and the a MS is represented by a triangle.
Parts of this work are published and submitted for patents: [Pub1, Pub5, Pub2, Pub3, Pub4, Pub6, Pub7, Pub8, Pub9, Pub10, Pub11, Pub12, Pub13, Pub14, Pub15, Pub16, Pub17, Pub18, Pub19, Pub20, Pub21].

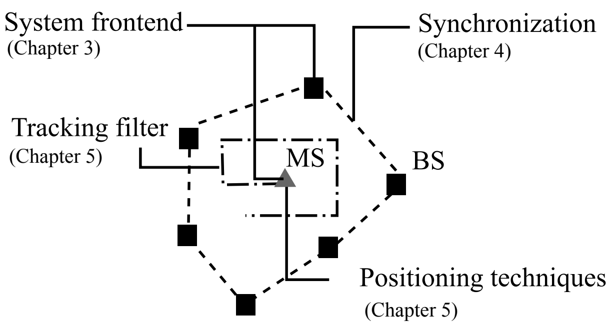

Figure 1.4.: Organization of the work in an illustrative track