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Indoor localization with audible sound — Towards practical implementation

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ABSTRACT

This paper presents an innovative evaluation and comparison of several methods and techniques necessary to implement an indoor localization system based on audible sound. Experiments were conducted in a room with conditions very close to possible practical application demonstrating that time delay estimation using generalized cross-correlation phase transform provides the best estimate to the distance to fixed anchors, and highlight the benefits of a new localization method entitled circle shrinking based on an optimization methodology. Of the three optimization methods tested, Gauss–Newton proves to be the most adequate, and among the three medium access methods evaluated, code division multiple access acoustic transmission provided the best results. A localization system combining these components and using only off-the-shelf hardware reached an average accuracy of 1.3 cm in the central area of the test room with an excitation signal-to-noise ratio as low as 7.2 dB, an almost unperceivable noise like audio signal. These results represent an advance of the state-of-the-art in indoor localization systems, pointing towards the possibility of widespread practical implementation with everyday use components.

1. Introduction

With the recent technological advances in mobile devices, there has been a strong growth in context-aware applications that passively or actively determine their locations [1]. Using appropriate algorithms these intelligent systems estimate the location and provide to the users some kind of information or service regarding specific geographically adapted content. Global Navigation Satellite Systems (GNSS) is nowadays seen as a standard service and assures this task in outdoor environments where there are satellites in line of sight. In contrast, indoor environments do not have a consensual technology established to achieve indoor localization with similar simplicity of use or implementation. All the available methods require at least one aspect that is not easily achievable in most practical situations. Some are still in a concept development phase, others are simply too expensive to implement. A rational approach to indoor localization would be one that uses information available everywhere without the need for additional specific setups. The presented approach uses public address (PA) loudspeakers as signal emitters that will allow a mobile device to localize itself. The typically present PA sound systems can be leveraged to provide additional functionality to allow users to determine their location through sound. Small modifications can be performed centrally minimizing large scale implementation costs, in essence, achieving a localization system like the established global positioning system (GPS), but this time, for indoor environments using acoustic signals. In a GNSS, the infrastructure is available in the sky worldwide. Conversely, in an indoor environment there is no suitable global signal available to receivers. Therefore, indoor spaces require specific signals, using special techniques, requiring

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custom hardware suitable to the indoor environment, based on the desired requirements of cost, precision, robustness or granularity. There is no "standard" RF signal like in the GPS example. Each type of environment or application has its own approach. In industrial environments, for example, buried cable systems emit RF signals, use laser beams or optical-based floor markers. For domestic, administrative, commercial or public environments proposed solutions rely, for instance, on radio technologies like Wi-Fi, optical signals, ultrasound waves or simply artificial vision. Up to now, no method, technology or technique has demonstrated the possibility to become a "standard" in indoor localization. Some are too costly, others are not robust enough and others require add-ons, tags or devices that will not facilitate an easy large scale dissemination.

The work presented here aims to reach a novel indoor localization system suitable for most situations and approaching the ease of use of GPS. To accomplish that, it employs audible sound (almost unperceivable) as the localization enabling signal considering that most public spaces already possess a PA sound system infrastructure. Smartphones can act as the localization enabling device offering acquisition hardware to capture audio without any patch, tag or other accessories. With both of these nearly ubiquitous components, an indoor localization system may be assembled without having any additional major cost or introduction of new equipment in the users' daily lives. Such a universal and user convenient approach, that considers these aspects simultaneously, has not been found in the literature so far.

For this type of application, it is of great importance to consider a simultaneous multi-user scenario. A user "timeslot" multiplexing approach for the localization is not desirable as it imposes smaller position refresh rates and may cause a waiting queue among users. Complementarily, when considering this signal type and the channel, one can understand that each audio contribution of a loudspeaker will be mixed with all the others in the receiver's point of view. There is no reserved single-access channel where communication would be much simpler. Thus, one of the key aspects when considering such a system is to evaluate which channel access method is more suitable for this audible sound approach in a shared medium. Three cornerstone communication methods used typically in radio frequency communication systems were evaluated: Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA) and Code Division Multiple Access (CDMA). An innovative comparison is performed among several methods required for achieving localization through the use of sound in the audible range. Audio signals are mechanical waves generated from vibrations within a medium. These signals travel through the channel very differently from the way electromagnetic waves do. In fact these types of signals do not interact much with people or objects (furniture, boundaries, etc.). Therefore, the known results of radio frequency approaches cannot be generalized without an additional study like the one provided in this paper. In an indoor scenario, this difference is reinforced due to the presence of extra physical boundaries (wall, floor and ceiling, for example). Channel effects like multipath, fading, interference are phenomena that behave quite differently while using audio signals. It is also very important to consider the drastically smaller propagation speed of sound, almost a million times slower. All these differences justify the need to evaluate methodologies without assuming that previously obtained results with other types of signals are valid for audible sound.

To achieve a functional setup valid for a real test bed comparison, the most relevant correlation methods to perform time delay estimation (TDE) are also evaluated. Localization estimation is discussed considering error minimization approaches based on classical least square estimation methods like Gauss–Newton, Newton–Raphson and steepest descent. Even a slight difference in performance may be important due to its frequent repetitive use in a localization system. This particular study can be of great interest depending on the application and in the conditions where processing capabilities are limited or localization estimation update rate needs to be higher.

The evaluation of all these requirements is necessary to study the possibility of using audible sound as the type of signal that will allow achieving localization. The experimental setup described in the paper emulates a possible real usage situation in almost all aspects. A 60 square meter room with 4 public address loudspeakers, people working, furniture, plaster walls, glass windows and environmental noise, is similar in many aspects to most possible applications where a pervasive indoor localization technology would be useful. Possible applications like museums, malls or public transportation hubs, are examples on where public address loudspeakers are typically present and would require minimum adaptation to such technology, lowering costs and improving the possibility of implementation. Larger areas like industrial spaces, where limited sound coverage and loud noise conditions could limit its usage, may have their own adjusted localization technology based on their specific requirements. Experimental tests were conducted statically to allow comparison between methods. Similar results are expected when moving at walking speeds as the Doppler Effect is not relevant because frequency changes in the received signals do not greatly affect the methodologies here employed regarding TDE, the most important component in localization based on time-of-flight.

This paper continues as follows: Section 2 presents the related work providing a general view on the state-of-the-art of indoor localization and explains the place and motivation of this novel approach; Section 3 introduces Indoor Audible Sound Localization, covering some of its most important issues and providing some possible answers; Section 4 describes the conducted experiments concerning the evaluation of all the components necessary to accomplish this type of localization. It also contains the results and comparisons between the choices to converge on a feasible audible sound localization system. Finally, Section 5 presents the conclusions and some future work on the subject.

2. Related work

Historically, radar and underwater sonar were the first modern localization applications. In the former, the distance from a faraway object at a certain angle is determined by the travel time necessary for an electromagnetic wave to go from