Information Fusion 45 (2019) 53–65

Contents lists available at ScienceDirect

Information Fusion

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

Simultaneous calibration and navigation (SCAN) of multiple ultrasonic local positioning systems

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ARTICLE INFO

Keywords:
Ultrasound
Local positioning system, Fusion
SCAN (Simultaneous Calibration and Navigation)

ABSTRACT

This paper proposes a Simultaneous Calibration and Navigation (SCAN) algorithm of a multiple Ultrasonic Local Positioning Systems (ULPSs) that cover an extensive indoor area. The idea is the development of the same concept than SLAM (Simultaneous Localization and Mapping), in which a Mobile Robot (MR) estimates the map while it is navigating. In our approach, the MR calibrates the beacons of several ULPSs while it is moving inside the localization area. The concept of calibration is the estimation of the position of the beacons referenced to a known map. The scenario is composed of some calibrated ULPSs that we denote as Globally Referenced Ultrasonic Local Positioning Systems (GRULPSs) that are located in strategic points like entrances covering the start and the end of a possible trajectory in the environment. Additionally, there are several non-calibrated ULPSs named Locally Referenced Ultrasonic Local Positioning Systems (LRULPSs) that are placed around the localization area. The proposal uses a MR with odometer for calibrating the beacons of the LRULPSs while it is navigating on their coverage area and go from one GRULPS to another. The algorithm is based on multiple filters running in parallel (one filter for each LRULPS and another one for the GRULPSs) that estimate the global and local trajectories of the MR (one trajectory for each local reference system of the LRULPSs) fusing the information related to the Ultrasound Signals (US) and the odometer of the MR. The position of the beacons of the LRULPSs are obtained by a transformation vector for each LRULPS that converts the local coordinates to the global reference system. This transformation vector is calculated using several points of a local trajectory and the corresponding points of the global one. The method is independent of the type of filter, provided that it works properly with non-linear systems and possibly non-Gaussian noise. Extended Kalman Filter (EKF), Unscented Kalman Filter (UKF) and H-∞ Filter have been tested, in simulations and real experiments, in order to compare their performance in this case.

1. Introduction

Since the GPS appeared and solved the outdoor localization, the challenge is the development of a similar system for indoor environments in terms of accuracy and availability.

The most extended technology to develop an indoor location system is Radiofrequency (RF) due to the low impact in the building infrastructure using the Access Points (APs) of the WiFi service [1–3]. The problem is that the accuracy of these kind of systems is not as ideal as the GPS due to the propagation characteristics of the RF signal in indoor environments. The majority of works that use this technology report mean errors of few meters with a high variance [4,5]. Nevertheless, some works present an accuracy of decimeters and centimeters deploying a high number of nodes and short-range communications [6], measuring the Time of Flight (ToF) with a nano-second resolution [7], or using multiple WiFi antennas [8].

Another technology less extended than RF is Ultrasound (US), whose advantage is its accuracy (centimeters in the most of works) due to the low propagation speed. Nonetheless, the disadvantage is the need of installing an external infrastructure and the reduced coverage area of the US signals (few meters). Each US infrastructure is composed of several beacons that form an Ultrasonic Local Positioning Systems (ULPS) [9,10]. Since its development, some upgrades appeared in order to improve the performance, such as the inclusion of codes in the emission of the beacons to avoid crosstalk and allow them to emit simultaneously [11].

For covering indoor extensive areas, a solution is the deployment of several ULPSs such as in [12]. Nevertheless, one of the problems is the calibration of the beacons of each ULPS, that is, the estimation of the position of each beacon related to the global map. Usually, the process for calibrating an Indoor Localization System (ILS) composed of a single LPS is manual and it is based on the use of a plumb to determinate the

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https://doi.org/10.1016/j.inffus.2018.01.005
Received 24 January 2017; Received in revised form 10 October 2017; Accepted 5 January 2018
Available online 06 January 2018

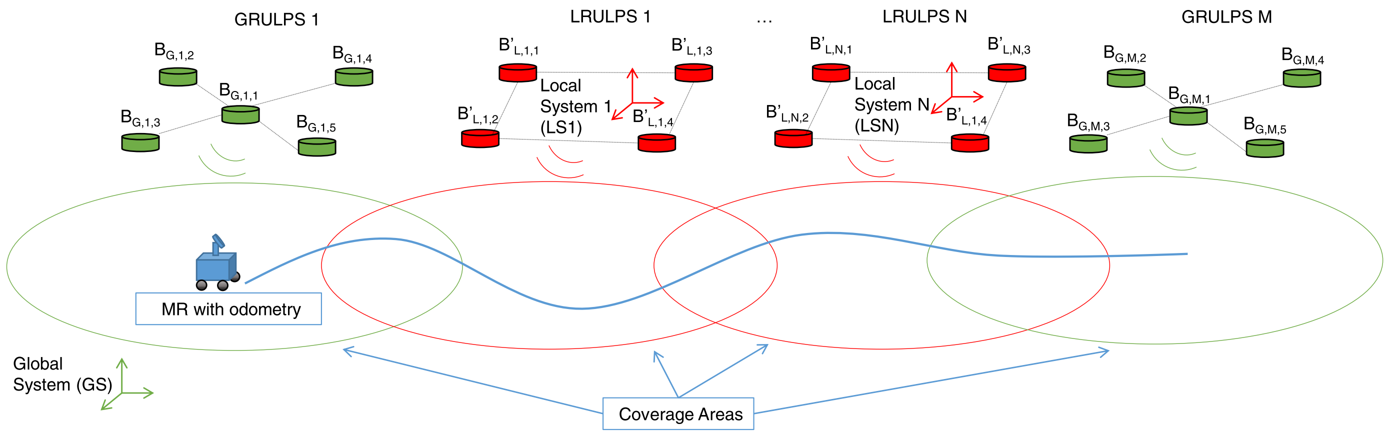

Fig. 1. Particular case of GRULPS and LRULPS structures, with five and four beacons, respectively.

beacons' projection on the floor and solve the 2D beacons' position using several distances from the projected points to some known reference positions of the environment like corners or different points on a wall. The height of the beacon is usually obtained by a laser meter. Other method that requires less effort than the first one is the use of the inverse positioning. The process is based on capturing several distance measures in known points on the floor (i.e. using a grid) and then, obtaining the position of the beacons using a localization algorithm [13,14]. In this case, it is necessary to know accurately the positions of a high number of measurement points. Normally, the selection of the floor points is arbitrary, but in [15] an algorithm determines the optimal points for beacons' calibration, minimizing the error. Recently, other method completely autonomous is based on the use of a MR with odometry for calibrating one LPS [16].

MRs are used in several researches for developing a map of indoor environments while they are navigating. This process is called Simultaneous Localization and Mapping (SLAM) [17–19], in which the robots are equipped with several distance meters to obtain measurements from the robot to the objects (walls, pillars, …) of the environment. Using these distances it is possible to make an estimation of the map while the robot is navigating and also computes its own trajectory. In this paper we propose the use of the SLAM concept to the autonomatic calibration of US beacons (that is, obtaining the coordinates of the beacons' positions) applying the method to multiple ULPSs instead of only to one [16]. We use the distances or difference of distances between the MR and the beacons to estimate the position of them. These distances are measured while the robot is navigating around the area of interest in which there are some non-calibrated ULPSs. Therefore, this proposal allows us calibrating multiple ULPSs automatically with a MR, avoiding the need of tedious manual methods. We denote the proposal as Simultaneous Calibration and Navigation (SCAN).

Regarding localization algorithms, for static positions or for the first position of the MR one of the most extended in literature is the Gauss-Newton one [20] for solving the non-linear equation system based on the distances between the receiver located on the MR and each emitter (beacon). These distances can be measured with ultrasound if there is a synchronization between the emitters and the receiver (spherical case). If there is no synchronization, then, the difference of distances, using one of the beacons as reference, are computed (hyperbolic case) [21].

In order to update the position of the MR fusing the available information (ultrasound signals and odometry in our case) it is very common the use of a filter [22]. The most representative for dealing with non-linear problems are Extended Kalman Filter (EKF) [23], Unscented Kalman Filter (UKF) [24], H-∞ filter [25] and Particle Filter (PF) [26]. The last one is more appropriate when the measures present a high variance and an unknown noise distribution such as localization systems based on radiofrequency (RF) or combination of different technologies [27]. For fusing information of measures based on ultrasound signals the most recommendable are EKF, UKF, H-∞ and other variations of them since the measures of these signals present a lower variance than the ones from RF and their noise distribution can be approximate to a zero-mean Gaussian distribution in some cases (not multipath).

As for the organization of the paper, Section 2 describes the architecture of the system and the objectives to be achieved; Section 3 shows the development of the proposed solutions describing the equations of the filters; Section 4 shows the simulated results; Section 5 shows the real experiments to validate the proposal; and, finally, Section 6 deals with some conclusions.

2. Statement of the problem

As described in the introduction, an ULPS allows locating a target with a high accuracy in a reduced zone. If an application requires locating a target in an extensive area using the ultrasound technology, the solution is the deployment of a set of ULPSs covering the full area for localization and navigation tasks. In our proposal we define two kind of ULPSs (Fig. 1). Globally-Referenced Ultrasonic Local Positioning System (GRULPS), in which the positions of its beacons $\mathbf{B}_{G,\,m}$ are known and referenced to the global reference system of the map, and they have been, for instance, manually calibrated. We suppose the errors of this method can be negligible, as they could be around millimeters using a laser plumb, that is below the error of distances measurement with ultrasounds. These GRULPSs can be located in strategic zones like the entrances of the environment, and Locally-Referenced Ultrasonic Local Positioning System (LRULPS), whose beacons' position $\mathbf{B}'_{L,n}$ are unknown with respect to the global reference system. On the other hand, in a LRULPS the arrangement of the beacons inside its structure is known and then we can reference their position regarding a local reference system (this locally-referenced positions will be included in the matrix $\mathbf{B}_{L,\,n}$). Several of these uncalibrated LRULPSs will be located covering areas between GRULPSs and the number and position of them can be changed along the time. Note that the sub-indexes G and L mean "global" and "local" respectively, while $m = 1,\ 2,\ \ldots,\ M$ and $n = 1,\ 2,\ \ldots,\ N$ denote the number of a particular GRULPS or LRULPS, respectively.

Each ULPS has to be composed of at least three beacons in the spherical positioning case (working with distances between the emitters and the receiver) or four beacons in the hyperbolic one (working with difference of distances).

The contribution of this paper is the development of an algorithm that allows calibrating all LRULPS beacons of the proposed structure with a Mobile Robot (MR) at the same time that it navigates and its trajectory is being obtained.

Fig. 2. shows the simulated scenario, where all beacons are placed on the ceiling, at a height of 3.5 m. The representation includes the