Measurement 128 (2018) 149–159

Contents lists available at ScienceDirect

Measurement

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

A prototype of static IR beacon-receiver positioning system based on triangulation method

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ARTICLE INFO

Keywords:
Positioning system
Triangulation
Indoor positioning
Local positioning
Infrared transmitter
Infrared receiver

ABSTRACT

The main purpose of each of the navigation systems is the determination of an object's position in a given reference frame. This can be realized in many different ways, and one of them is a triangulation method that is based on known reference object positions. This paper presents a new triangulation system that has one major difference from existing systems: the lack of mechanical moving parts such as motors, rotating lasers or rotating diodes. The measuring device without moving parts is easier to implement, energy-efficient and more resistant to disturbances such as vibration. The work presents a detailed description of the prototype of the static positioning system. Every component of the system, starting with hardware configuration and ending with computational algorithms, is fully described and discussed. The accuracy of the system has been experimentally verified with very good results - the accuracy is comparable to existing systems with mechanical moving parts. The experimental results not only showed the proper work of the system, but also revealed new facts that are foreseen to further improve the measurement accuracy of the device.

1. Introduction

The main purpose of each of the navigation systems is the determination of an object's position in a given reference frame. The celestial navigation was already known in ancient times as Homer described in the Odyssey [1]. A very interesting example of an early navigational system is the system used by the Polynesians to travel between islands. They used the Marshall Islands stick chart which represented major ocean swell patterns disrupted by islands [2]. The next step in the development of navigation was the invention of the compass in China, which appeared in Europe in the twelfth century [3]. The invention of the sextant in the 16th century gave rise to precise navigation [4]. The development of orbital flights has completely changed the face of navigation. Today, almost all navigations (maritime, aviation and land) are based on the GPS. Despite its universality, the Global Positioning System has some limitations: about 1 meter accuracy and a lack of indoor area coverage. To make it possible to navigate inside buildings or to improve the navigation precision, Local Positioning Systems (LPS) have been constructed.

1.1. Methods of determining an object's position

There are two major methods of determining an object's position in a given reference frame [5,6]. The first method consists in determining the relative object's position (called Dead-reckoning) and can be calculated by for example odometry or inertial navigation. This method is accurate in a short span of time but unfortunately its accuracy significantly decreases with time (due to integration errors, wheelbase uncertainty, wheel slippage, etc.) [5]. In addition, such a system requires the knowledge of the initial conditions which in many cases are not known.

The second method is to designate the absolute position (called Reference-based systems) based on the known reference object's positions. Absolute positioning systems are more accurate than the mentioned above relative positioning system and therefore are widely used in navigation. In many situations the two methods mentioned above are used simultaneously in order to improve the accuracy (for example inertial navigation and GPS signal connect together via a Kalman filter). The most famous representative of absolute positioning systems is the GPS, in which satellites are these known reference objects. In many situations, the GPS system gives sufficient accuracy. There are also methods to improve the accuracy of GPS systems up to centimeters. These systems called RTK (Real-Time Kinematic) use ground reference stations with known locations to improve the GPS accuracy [7,8]. Unfortunately, the RTK systems do not solve the problem of lack of signal inside buildings. The annual thematic conference *The International Conference on Indoor Positioning and Indoor Navigation* or the annual competition *Microsoft Indoor Localization Competition* show how important the issue of the indoor navigation is.

To determine an object's location in absolute positioning systems,

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https://doi.org/10.1016/j.measurement.2018.06.039
Received 12 October 2017; Received in revised form 24 May 2018; Accepted 20 June 2018
Available online 22 June 2018
0263-2241/

geometric relationships are most commonly utilized. There are also systems based on the measurement of the magnetic vector field where the source position of this field is known [9]. It can be said that the majority of absolute positioning systems use one of two processes to designate an object's position. These processes are called: trilateration and triangulation [10].

1.2. Trilateration

Trilateration is the process of determining an absolute object's position based on the measurements of the distances to known objects hereinafter called beacons. The distance between an object and the beacon is calculated indirectly on the basis of time of flight (TOF) of the signal (radio frequency signal (RF) or ultrasonic signal) or the time-difference of arrival (TDOA) of the signal and knowledge of the propagation speed of this signal in ambient space. The most popular RF trilateration method is based on the UWB (ultra wideband) technique where a communication channel spreads information out over a wide portion of the frequency spectrum, which makes the calculation of time of flight more precise [11–14]. The accuracy of UWB systems is about 20–30 cm [15]. Another RF trilateration method is so called a Fingerprint location method which is based on the Wi–Fi received signal strength (RSS). It uses distribution characteristic of Wi–Fi RSS in the space to estimate an object's location [16–19]. The great advantage of the Fingerprint method is the use of an already existing IT infrastructure (routers, access points). The disadvantage, however, is the need to access the database to determine the position based on the RSS strength. The accuracy of the Fingerprints systems is about 1–5 m [15]. Another family of positioning systems are ultrasonic systems [20–22]. The ultrasonic systems are more accurate than radio systems (due to the fact that sound is slower than light) but have a smaller coverage area. The accuracy of ultrasonic systems can be up to 1 cm [15].

The disadvantage of positioning systems which are based on the trilateration method is the inability to calculate the object's orientation (heading) except in situations where the object is moving (as in the case of the GPS). However, the great advantage of this kind of system is the 3D positioning, which in the case of triangulation is a rarity.

1.3. Triangulation

Triangulation uses other geometric dimensions, namely angles. It is the process of determining an object's position by measuring the angles φ_i between the object and the known locations/beacons B_i (see Fig. 1). Such systems, unlike trilateration, are able to determine an object's position and its orientation directly and simultaneously. Triangulation systems can be grouped according to the principle of their operation and construction. The first group uses a mounted on-board laser beam rotating at the horizontal plane and illuminating retroreflective beacons. The beacons simply reflect incoming light back to the mobile robot sensor and based on this signal and knowledge of the laser angular position, the beacon-mobile robot angle is calculated [23,24]. In this system the beacons are indistinguishable, so the system requires knowledge of the initial conditions at every system initiation.

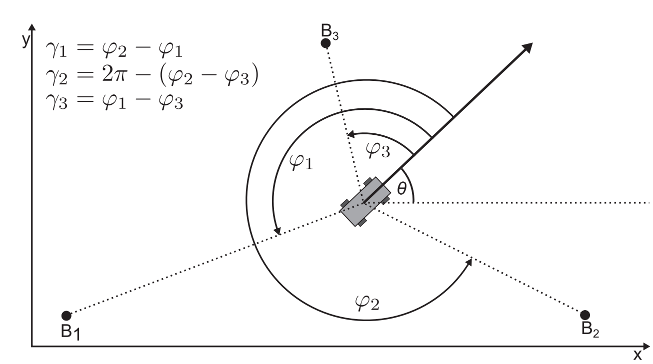

Fig. 1. 2D plane triangulation setup. B_i are the beacons, φ_i – beacon's angle measurements relative to the robot heading θ, γ_i – angles between beacons.

Another group of triangulation systems is very similar to the previous one. The difference is the unique beacons. This has been achieved through the use of an additional communication channel (typically an RF channel). When the laser's light hits the beacon, the beacon resends an identification message: "Beacon No. x was hit" to the mobile robot through an RF channel [23,25]. This solution is therefore more reliable than the previous one because it does not require knowledge of the initial conditions. There are also solutions when the laser beam mounted on the beacon rotates and illuminates the surrounding space. In this case the receiver is a circular photo sensor array on the mobile robot [26]. Some triangulation systems use an infrared spectrum instead of a visible spectrum e.g.: active beacons emitting infrared light and a rotating infrared receiver on the mobile robot [27].

1.4. Research motivation

The accuracy of angle measurements, which directly affects the accuracy of an object's position, for the triangulation systems mentioned above is within 0.1°–1°. From a constructional point of view, all these systems have a common feature: mechanical moving parts such as motors, rotating lasers or rotating diodes. These moving elements require an additional power supply, complicate the construction, and wear out over time. So a question arises: is it possible to build a triangular positioning system without moving parts, but one that is characterized by a similar accuracy to those with moving parts? The lack of rotary receiver/transmitter elements in triangulation systems makes it necessary to simultaneously measure the whole of the 360° horizontal field. Such static triangulation systems exist but they are rather used by robots swarm formation for relative positioning and not for precise absolute positioning [28,29]. A full range horizontal field measuring system was also used in golf greens mower [30] but the circular photodiodes array was only used to compute the orientation angle, not both: orientation and position.

To answer the question posed above a static triangulation systems was designed, built and then tested. The goal of the presented study is to show a new approach to the triangulation system where an object's heading and position is computed by an infrared system which does not contain any mechanical moving parts.

The next chapter of this paper describes the functional principle of the new triangulation system. The hardware configuration of the entire system is described in detail in Section 3. Chapters 4, 5 and 6 contain a description of the calculation algorithms necessary for proper operation of the positioning system. The next two sections show the results obtained during the experiments: Section 7 describes the method of determining the coverage area of the constructed static IR beacon-receiver system. Finally in Section 8, the experimental verification of the positioning system was described and discussed. The presented positioning system is based on angles measurement, so the performance of the system should be qualified in terms of angles (variance and bias of the measured angles), and this was of course performed. The main purpose of the system, however, is to determine an object's position, and therefore the analysis for the accuracy of the position was also carried out. The preliminary results of the presented system were already shown in [31]. Compared to the preliminary results, this paper has been enriched with new issues:

- Extension of the description of the hardware and software
- A new beacon identification algorithm,
- Determination of the coverage area of the positioning system,
- Investigation of the angular isotropy of the measurement device,
- Determination of the error maps of the positioning system.