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Enhancing workers safety in worksites through augmented GNSS sensors

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ABSTRACT

Human-assistive wearable technologies can monitor the position of a worker in a critical worksite and improve his safety by raising warnings when he is in a dangerous zone. In railway worksites, it is observed that GNSS localization is not applicable due to the relevant localization errors, which are only partially attributable to the specific characteristics of the worksite. Besides, alternative solutions that rely on the support of anchors have the drawback of lengthening the set-up and dismantle time of the worksite. To provide safe localization of railway trackside workers, a system that exploits augmented-GNSS wearable sensors is proposed. Each sensor includes a GPS receiver capable of sharing its coordinates with the other sensors, and is further complemented with a low-cost multi-way distance meter to measure its distance from the other sensors. The main attention is paid to the data fusion approach adopted to improve the accuracy of the position estimate by combining the relative distance measurements to the GPS coordinates.

1. Introduction

Self-localization capability is a highly desirable characteristic of mobile electronic devices. It enables a myriad of applications such as inventory management, intrusion detection, road traffic monitoring, health monitoring, reconnaissance, surveillance [1]. Nonetheless, self-localization is also an attractive mean to guarantee safety of people or moving assets, when they operate in critical areas in which there is a significant risk of being struck by objects or vehicles [2].

The most straightforward approach to achieve self-localization relies on the Global Navigation Satellite System (GNSS) i.e., satellite-based localization as the Global Positioning System (GPS [3]). However, in several environments, satellite-based localization can result challenging, because of specific characteristics of the environment, or difficulties of assuring tight accuracy requirements: GNSS sensors localization errors can in fact be even greater than a few meters [4].

An alternative solution is adopted in air traffic surveillance applications. Specifically, a dedicated technology, known as Automatic Dependent Surveillance-Broadcast (ADS-B) [5], is preferred to GNSS or radar based systems to accurately track airplanes in flight and on the ground. Airport surface surveillance takes advantage of ADS-B to assure safety of workers by providing situational awareness about the airport surface dynamics during cargo and shuttle operations. Unfortunately, ADS-B solutions are less flexible that GNSS ones and cannot be easily reproduced outside the airport ramp; typically, they cannot be enabled in worksites either for budget limitations or technical constraints.

More and more often, GNSS based solutions are combined with other systems in order to obtain increased accuracy and allow workers position tracking in critical worksites. As an example, in railway worksites effective tracking has been managed through a GPS system that combines GPS data with information from electronic fences placed within the worksite area [6]. Specifically, the fences data are collected from the communication layer, and fused with the GPS data in the localization component [7]. This allows determining with high accuracy if the worker is in a safe (green) or unsafe (red) zone. However, the set-up and dismantle time of fences is a significant limitation: such a solution is impractical when the worksite is established only for a short time or when it is frequently moved along the railway [8–10].

In this paper, a GNSS-augmentation approach is proposed to improve self-localization of workers, with the specific objective of detecting if they are located in a dangerous area. The focus of the work is the railway domain, although other domains could be targeted as well. In the railway worksite, ground infrastructure may not be available due to the characteristic of the surrounding environment. Cost constraints usually force to disregard expensive equipment, as well as anchor-based systems, since they affect the set-up and dismantle time of the worksite.

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The main target is therefore the definition of a solution for human-assistive wearables, that can be realized by means of devices with low cost, reduced weight, and limited power consumption such that daily operability can be assured.

The considered system is composed of wearable GNSS sensors that include multi-way distance sensors and allow data sharing. Each wearable sensor is assigned to a worker and performs fusion of the GNSS receivers data and its own multi-way distance sensor data to provide an estimate of the positions of the workers. The proposed GNSS augmentation approach is analytically presented in Section 2. The achievable performance is evaluated and compared to that offered by GNSS in Section 3, where it is shown that thanks to the proposed solution it is possible to identify workers in safe and unsafe zones, reducing the number of false and missed alarms with respect to systems exclusively based on the GNSS technology. Also, compliance with standard regulations and applicability to the railway domain are discussed in Section 4. Finally, concluding remarks are given in Section 5.

2. Proposed GNSS augmentation approach

The proposed approach exploits a data fusion algorithm to combine measured data and estimate the positions of the workers. Each worker is equipped with a GNSS receiver and a distance sensor, included into a single device. For the sake of clarity, a simplified version of the data fusion algorithm is first described under the assumption of fully connected network i.e., each device can measure its distance from all the others. Later on, the assumption is removed and the proposed algorithm straightforwardly improved.

The proposed algorithm computes the absolute positions of all the workers by combining the data measured by all the devices. In detail, the vector of the measurement data $\mathbf{y}$, includes the data from the GNSS receivers and the distance sensors. For a team of N workers, each one equipped with a correspondent device, the number of elements in the vector $\mathbf{y}$ is $3N + N(N-1)$, since there are $3N$ coordinates from the GNSS receivers, and $N-1$ distance values from each distance sensor.

The vector $\mathbf{y}$ is related through an observation model $\mathbf{h}$ to the vector of the positions of the workers $\mathbf{x}$, which includes $3N$ elements, by:

$$\mathbf{y} = \mathbf{h}\mathbf{x} + \mathbf{v} \tag{1}$$

where vector $\mathbf{v}$ represents additive Gaussian noise. The observation model $\mathbf{h}$ is non-linear since its coefficients depend on the positions of the devices. If the initial positions $\mathbf{x}_0$ of the workers are roughly known (to this end the data offered by the GNSS receivers can be considered without any data fusion improvement), the knowledge of their actual positions can be improved and tracked at the successive time epochs by solving linear problems, which include the fusion of the data coming from GNSS receivers and the distance sensors. In fact, Eq. (1) can be linearized in the neighboring of the initial state $\mathbf{x}_0$ according to:

$$\mathbf{y}_1 = \mathbf{y}_0 + \Delta\mathbf{y}_1 = \mathbf{h}(\mathbf{x}_0)\mathbf{x}_0 + \mathbf{J}_\mathbf{h}(\mathbf{x}_0)\Delta\mathbf{x}_1 \tag{2}$$

where the current measurements $\mathbf{y}_1$ are represented in terms of expected values $\mathbf{y}_0$, evaluated by means of the observation model as $\mathbf{y}_0 = \mathbf{h}(\mathbf{x}_0)\mathbf{x}_0$, plus a difference, $\Delta\mathbf{y}_1$. This difference is linearly related to a correction term $\Delta\mathbf{x}_1$ for the positions of the workers through the Jacobian of the observation model, evaluated in the initial state $\mathbf{J}_\mathbf{h}(\mathbf{x}_0)$. The positions of the workers will be evaluated at the generic time epoch k as $\mathbf{x}_k = \mathbf{x}_{k-1} + \Delta\mathbf{x}_k$, where the correction term $\Delta\mathbf{x}_k$ is gained by inverting the linear problem:

$$\Delta\mathbf{y}_k = \mathbf{J}_\mathbf{h}(\mathbf{x}_{k-1})\Delta\mathbf{x}_k \tag{3}$$

In particular, $\Delta\mathbf{x}_k$ is obtained using a best linear unbiased estimator, which is substantially a weighted least square estimator, designed to provide a maximum likelihood estimate. To this end, Eq. (3) is inverted using an auxiliary weighting matrix, known as measurement information matrix, which is the inverse of the covariance matrix $\mathbf{R}$ of the noise affecting the measured data. As shown in [11], the best linear unbiased estimate of $\Delta\mathbf{x}_k$ is:

$$\Delta\mathbf{x}_k = (\mathbf{J}_\mathbf{h}^T\mathbf{R}\mathbf{J}_\mathbf{h})^{-1}\mathbf{J}_\mathbf{h}^T\mathbf{R}^{-1}\Delta\mathbf{y}_k \tag{4}$$

where the superscript T stands for transpose operator. In Eq. (4) all the measured variables are supposed to be independent from each other and affected by Gaussian noise of known variance; the Jacobian $\mathbf{J}_\mathbf{h}$ is evaluated considering the positions of the workers at the time epoch $k-1$.

It is worth noting that the time epoch grid characterizing the processing operations can be much finer than that characterizing the measurements updates. In this case, the system benefits of the additional iterations of the proposed algorithm that definitely improve the estimates. To reduce power consumption, the iterations can be repeated until a stopping criterion, based on the norm of $\Delta\mathbf{x}_k$, is met; then the system is put in sleeping mode waiting for the update of the measurement data $\mathbf{y}_{k+1}$, which will allow to compute $\Delta\mathbf{y}_{k+1}$ and restart the processing. In more realistic scenarios, the observation model should be dynamically configured, by including or excluding some rows, when the distance sensors data or GPS coordinates are not available. In fact, the distance sensors have a limited range of operation, and can even fail their task if the target is within the operation range but not in line of sight. Consequently at the generic time epoch only a subset counting M out of $N-1$ distances can be available from each distance sensor. This implies that the wearable devices use differently-configured observation models.

3. Performance analysis

Manufacturers assess their GNSS receivers performance distinguishing between horizontal and vertical directions. The latter performance is typically much worse than the former; fortunately, accurate knowledge of the vertical position is not crucial in the great majority of cases.

The parameters commonly used to express the performance in the horizontal plane are: circular error probable 50% (CEP50), radius 95% (R95), root mean square (RMS), and two times the distance of RMS (2DRMS) [12]. These parameters represent the radius of a circular region in the horizontal plane, where the positions gained by the receiver during on-field experiments are found with a given probability, that is 50% for CEP50, 95% for R95, 68% for RMS and 95% for 2DRMS. The performance in the vertical direction is expressed as a factor times that of the horizontal plane [13], and has to be intended as the length of a linear segment where the vertical position is found with the same confidence of the horizontal parameter.

As an example, low-cost GPS-receivers available in smartphones have a typical R95 value less than 4.9 m under open sky; their accuracy however worsens near buildings, bridges, and trees. Compact receivers with built-in antennas, which are commonly used to interface workstations and portable notebooks, specify 2.5 m CEP and 2 m CEP when complemented with basic satellite based augmentation systems (SBAS). At the state-of-the-art real-time positioning within a few centimeters is also possible by exploiting ground based augmentation strategies (GBAS). These systems should not be considered as competitors of the proposed system, since they rely on dedicated ground infrastructures characterized by huge costs.

In detail, experimental assessment of GNSS receivers performance requires gathering a 24-h, or longer, data set of positions of static GNSS receivers, in order to log the diurnal environmental effects (e.g. ionosphere) and visibility conditions of GNSS satellites. The data set of positions is then compared either to certified surveyed reference markers or to the centroid of the same data set to estimate the performance parameters.

It is worth noticing that these performance parameters cannot be regarded as absolute indicators of the positioning uncertainty, which is not uniquely related to the quality of the receiver. They are instead