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Improving data fusion in personal positioning systems for outdoor environments

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ABSTRACT

A fault detection and correction methodology for personal positioning systems for outdoor environments is presented. We demonstrate its successful use in a system consisting of a global positioning system receiver and an inertial measurement unit. Localization is based on the dead reckoning algorithm. In order to obtain more reliable information from data fusion, which is carried out with Kalman filtering, the proposed methodology involves: (1) evaluation of the information provided by the sensors and (2) adaptability of the filtering. By carefully analyzing these factors we accomplish fault detection in different sources of information and in filtering. This allows us to apply corrections whenever the system requires it. Hence, our methodology consists of two stages. In the first stage, the evaluation is conducted. We apply the principles of causal diagnosis using possibility theory by defining states for normal behavior and for fault states. When a fault occurs, corrective measures are applied according to empirical knowledge. In the second stage, the consistency test of the filtering is performed. If this is inconsistent, principles of adaptive Kalman filtering are applied, which means the process and measurement noise matrices are tuned. Our results indicate a reasonable improvement of the trajectory obtained. At the same time, we can achieve consistent filtering, to obtain a more robust system and reliable information.

1. Introduction

In the last decade, location systems for users have become increasingly important largely due to the availability of mobile systems and the rapid increase in applications and services that require a very good location system. The reliability of the information obtained from a location system depends to a large extent on the information provided by the positioning system. In this paper we define the positioning system as the system designed only to provide position and orientation of a person.

As any multisensor system, a *personal positioning system* (*PPS*) may be affected by numerous interferences that can cause it to fail and reduce its quality characteristics, such as reliability, availability, and accuracy. Fault detection and decision-making can be useful to overcome these problems, which are still a challenge for PPS. The advantages of fault detection and decision-making have been widely demonstrated in location systems for other target applications such as robotics and vehicle navigation.

In this paper a new *methodology for fault detection and correction* (*MFDC*) in personal positioning systems for outdoor environments is presented. This methodology is based on different traditional concepts involved in both PPS and location systems for other applications such as robotics and vehicle navigation. We use concepts such as the *dead reckoning* (*DR*) algorithm [1], data fusion using Kalman filtering [2] and its evaluation.

The methodology developed here mainly employs principles from *causal diagnosis using possibility theory* (*CDP*) [3] and adaptive Kalman filtering; to the best of our knowledge, this is a new combination for pedestrian positioning systems. By doing so, we increase robustness and reliability of the PPS and improve the autonomy of the system by correcting information whenever possible.

This paper is structured as follows: in Section 2 background and related work are presented. Section 4 presents the foundations – causal diagnosis using possibility theory, as well as evaluation and correction of Kalman filtering. Sections 5 and 6.3 show the dead reckoning algorithm and the models proposed for Kalman filtering, respectively. The methodology for fault detection and correction is proposed in Section 6. Section 7 presents the tests carried out and the discussion of the results. Section 8 contains the main conclusions and future work.

2. Background and related work

The precise determination of a user's position outdoors is a crucial task for a countless number of applications. Such applications

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include navigation systems for users, which can be used for rescue work (e.g. location of a firefighter in the front line of a fire), tourism (e.g. a tourist guide for an area of interest) or tracking workers (e.g. outdoor path checking in an industrial environment), among others. There are also prototypes being used in mixed reality applications [4].

In navigation systems, the positioning system is a fundamental component. Its design implies the integration of different disciplines and technologies as needed by the application in order to improve its quality characteristics, such as *robustness, reliability, accuracy, and autonomy*.

Outdoors, the *global positioning system* (*GPS*) is helpful, but is not always accurate enough to locate a person. It has disadvantages associated to the problem of an obstructed or attenuated signal in addition to the multipath phenomenon [5]. Therefore, PPS are very often designed as integrated multisensor systems in which combinations of GPS and inertial (accelerometers, gyroscopes) or magnetic (compass) technologies, are conducted [1,6,7]. In these systems the positioning algorithm is based on the dead reckoning principle (DR), which has been widely used due to its applicability to self-contained systems [8]. Sensor technologies and DR are subject to errors (e.g. perturbations in the environment), which should be evaluated and corrected. Thus, the study of methods that allow us to reduce and correct or eliminate those errors is highly relevant.

The DR algorithm requires information of the distance traveled by the object and the object's orientation, in order to obtain the object's position. In the human case, Levi and Judd [1] proposed a method based on human locomotion [9], in which the distance traveled is calculated by combining the stride length and step count of the pedestrian. To identify the step occurrence and to calculate the stride length, the approach of Levi and Judd consists in placing accelerometers on the user's torso in order to identify the pattern of the vertical (*z*-axis) acceleration while the user walks. This approach is applicable for step frequencies between 0.5 and 3 Hz. Additional studies showed that horizontal (i.e. forward) acceleration also presents a pattern that can be used to detect steps [10]. Then, the stride length is estimated by means of a linear relationship established between the step frequency and stride length. In another approach to determine the stride length, Ladetto [11] proposed a method based on linear regression that uses step frequency and vertical acceleration variance. With the same parameters, in addition to ground inclination, Cho and Park [12] proposed the use of neural networks to calculate stride length with the sensors being mounted on the user's foot. Jirawimut et al. [6] proposed to correct the step length by using the GPS data and estimating the errors through an extended Kalman filter. In order to increase robustness to the process of obtaining the stride length, we detect the step using both vertical and horizontal linear acceleration and we use a neural network to determine the stride length, whose errors will be estimated using an extended Kalman filter.

To determine the orientation or azimuth, data of gyroscope and digital compass are usually fused. The aim is to overcome the disadvantages presented for each sensor, individually. Namely, azimuth provided by a gyroscope presents errors that grow over the time, while azimuth provided by a digital compass is highly affected by magnetic disturbances. Ladetto and Merminod [13] proposed a method to combine both sensors through a Kalman filter, thus the compass is used to determine the bias of the gyroscope and the gyroscope is used to compensate the azimuth when the compass is affected by disturbances. A different approach was presented by Jirawimut et al. [6]. While GPS data are available, compass bias is estimated through an extended Kalman filter, in order to update the azimuth to DR.

Despite Kalman filtering is a good mechanism to estimate the errors of the information required by DR, a number of aspects must be taken into account when it is applied [2]. To get good results, one has to be perfectly familiar with the system model and the true initial values for process (Q) and measurement (R) noise covariances should be known. First, in practice it is difficult to obtain a model that shows the behavior of the whole system and it is not always possible to include models of all the interferences that can affect a system. Second, we often have very little or no knowledge at all of the values of Q and/or R. As a result, the statistical conditions of the variables may not be fulfilled, thus violating the basic principles of the filter [14]. In the fields of robotics and vehicle navigation, a combination of Kalman filtering, fuzzy logic and/or neural networks is often used to improve the estimated information by applying fault detection or an adaptive mechanism [15–20]. These methods mainly focus on evaluating the residuals of the filter. However, an evaluation of the measurements is also required, because there may be reflections in the signals that can also affect the filter performance [21], e.g. reflection in the GPS signal.

Therefore, we present a methodology that evaluates and corrects the information in PPS, which is denominated as *methodology for fault detection and correction* (*MFDC*). A general description is presented in next section. Briefly, the methodology introduces several concepts into personal positioning systems (PPS), such as fault detection by applying CDP, testing the consistency of Kalman filtering, and a correction mechanism based on tuning matrices R and Q. For this type of application, these are new concepts. Specifically, causal diagnosis has not been used in navigation systems and consistency test with tuning the matrices R and Q (as we did it) has not been used for PPS.

3. General description of MFDC

Our PPS is compounded of a GPS receiver and an IMU. Localization is based on the dead reckoning algorithm. For this system, we propose a methodology for fault detection and correction. It has two main stages: *the diagnosis subsystem and the filtering and evaluation subsystem*. Fig. 1 illustrates the flow diagram of MFDC.

As mentioned in Section 2, it is relevant to detect reflections in the signals or abnormal measurements before introducing them to the Kalman filter. In the first stage of the methodology we therefore define a *diagnosis subsystem* to identify measurements that are not appropriate according to the empirical knowledge. The diagnosis is applied to the information provided by a GPS receiver, the azimuth (provided by an IMU) and step occurrence. This subsystem uses causal diagnosis based on possibility theory (CDP), which can be used to identify normal and abnormal behaviors in a process, through the expert's knowledge representation [3]. Applications for fault-diagnosis with this framework can be found in [22–24]. Subsequently, if a fail occurs (a measurement evaluated as not appropriate) a rough correction is conducted.

In the second stage, Kalman filtering and the evaluation mechanism are applied. The evaluation mechanism is based on the consistency test [14], which is combined with principles of fuzzy logic [19]. As in the first phase, a correction subsystem is also implemented by applying some foundations of adaptive Kalman filtering [18,25], such as adjusting matrices Q and R.

Finally, once the information required by DR is corrected, the user's position is determined.

4. Methods: foundations

In the following, the basics (used in this work) of CDP and adaptive Kalman filtering are briefly described.