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Verified stochastic methods in geographic information system applications with uncertainty

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ABSTRACT

Modern localization techniques are based on the Global Positioning System (GPS). In general, the accuracy of the measurement depends on various uncertain parameters. In addition, despite its relevance, a number of localization approaches fail to consider the modeling of uncertainty in geographic information system (GIS) applications. This paper describes a new verified method for uncertain (GPS) localization for use in GPS and GIS application scenarios based on Dempster-Shafer theory (DST), with two-dimensional and interval-valued basic probability assignments. The main benefit our approach offers for GIS applications is a workflow concept using DST-based models that are embedded into an ontology-based semantic querying mechanism accompanied by 3D visualization techniques. This workflow provides interactive means of querying uncertain GIS models semantically and provides visual feedback.

1. Introduction

Robot localization and motion planning in a complex environment is one of the fundamental tasks in robotics. The DAAD Summer Academy on Guidance and Control of Autonomous Systems held at the University of Duisburg-Essen in 2005 brought together interested students and well known experts to focus on advanced control techniques for autonomous systems. The academy proceedings chapter "Environment Modeling and Navigation of Autonomous Robots" [1], documents the state of the art in "Mobile Robots in Complex Environments: Localization and Mapping" by Schlegel, who describes the global positioning problem and the position tracking problem, as well as in Burgard's fundamental contribution, "Probabilistic Techniques for Mobile Robots". The ingredients are maps of a stochastic environment, the robot's initial position and direction (x, y, ϑ) (pose p_{t-1} at time $t = 1$), control inputs u_{t-1}, and a recursive process for finding the robot's pose at time t. The autonomous robot can look around using vision systems, beacons, landmarks, or GPS to get an indication of its location. Thus, a sequence of fused noisy sensor measurements leads to observations z_t and is used to correct the robot's pose to p_t, including aleatory uncertainty in the dynamic and observational models.

The general localization problem was originally described by Thrun et al. as a Bayesian estimation problem [2]. It consists of estimating the probability density over the space of all locations. Their "Markov Localization Framework" evaluates dynamic processes and information from multiple sensors to build the robot's belief to be at a certain location to a certain degree. Another extensive presentation is given by Rudy Negenborn in his thesis "Robot Localization and Kalman Filters: On Finding Your Position in a Noisy World" [3]. Using the Kalman filter approach is one way to apply a Bayesian filter technique as an optimal least mean squares (LMS) estimator of a linear Gaussian system or as a non-linear extended Kalman filter (EKF), when the step function is non-linear according to a non-linear robot's kinematic model (sudden velocity and direction variations [4]) and probability distribution parameters are subject to change. As Burgard stated in [2], particle filters, hidden Markov models, dynamic Bayes networks, and partially observable Markov decision processes (POMDPs) are other familiar methods. In these approaches the Markov assumption guarantees that based on the current state of the robot, future and past states are conditionally independent of one another, and recursive Bayesian updating can be used to efficiently propagate the pose distribution.

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Localization using only the Global Positioning System (GPS) suffers from uncertainty due to environmental disturbances and errors occurring in GPS signal measurement. Nonetheless, a number of applications use GPS-based localization for a variety of purposes, such as navigation of robots [5] or localization of images [6]. Over time, various algorithmic approaches have been developed to compensate for errors in measurement, especially in the context of widely used GPS localization, such as an adaptive Kalman filter-based approach implemented using a fuzzy logic inference system [4], or a combination of GPS measurements with further sensory data as described in [7]. However, conventional Kalman filters have been widely used in GPS receivers, as is explained in [4], which characterizes the unrealistic assignment of constant noise levels in GPS-based localization dedicated to a mobile robot operating in rough terrain. The authors propose a real-time adaptive algorithm for GPS data processing based on the observation of residuals. They demonstrate that the algorithm is very robust with regard to sudden changes in the vehicle's motion and reduces positioning error by up to 75%. Burigat et al. [8] recommend several means of improving accuracy through additional sensor data and advocate that external information be integrated into the position calculation process. They cite, among other systems, the Wide Area Augmentation System (WAAS), differential GPS (DGPS), and assisted GPS (AGPS), all of which are based on transmitting additional information about sources of the location error (e.g., clock drift, ephemeris, or ionospheric delay). Nevertheless, these approaches need additional infrastructure (e.g., ground stations, wireless cellular networks) and compatible receivers.

Another method for improving position accuracy is based on the use of inertial navigation systems (INS), i.e., self-contained systems equipped with sensors such as accelerometers and gyroscopes to measure the position, velocity and altitude information of moving objects, excluding GPS measurements. Even if efficient localization algorithms exist when solutions exploiting GPS are not available, INS cannot replace GPS as a navigation system due to error accumulation over time. Thus, GPS and INS are often used together to combine the long-term accuracy of GPS with the short-term accuracy of INS; together, they manage to overcome the limitations of GPS–at least to a certain degree.

In their paper [9], Maier and Kleiner propose a novel approach for incorporating multipath errors into the conventional GPS sensor model by analyzing environmental structures from point clouds generated online. They report that reliable GPS-based outdoor navigation systems have been achieved in the past, for example, during the DARPA Grand Challenge and DARPA Urban Challenge [10].

In recent years, important advances have been made in combining guaranteed interval methods with random approaches. The outlier minimal number estimator (OMNE) proposed by Walter et al. [11] has been introduced to make parameter bounding robust to such outliers, and a new algorithm GOMNE, based on set inversion via interval analysis, provides a guaranteed OMNE, which is applied to the initial localization of an actual robot in a partially known two-dimensional environment. This work was recently extended in [12] by Bilenne. The author describes two algorithms: the first relying on the propagation of all the measurement intervals as a variant of the GOMNE algorithm suggested and the second as a fault-tolerant version of the prediction-correction interval estimator proposed by Jaulin, Kieffer and Walter in an earlier work [13]. Ashokaraj [14] describes a new approach for mobile robot navigation using an interval analysis (IA)-based adaptive mechanism for an EKF. The IA robot position estimated with ultrasonic sensor measurement is used as an adaptive mechanism to correct the errors in the EKF robot position estimation. Constraint propagation and contractors or enhanced interval arithmetic, such as affine arithmetic, can be used to decrease the high computational complexity.

It has been shown in recent years that Dempster-Shafer theory (DST) can be an alternative to probability theory in early design stage dependability predictions. Expert estimates can be represented, input uncertainty is propagated through the system, and prediction uncertainty can be measured and interpreted. As stated in [15, p. 27], "The joint probability density function (PDF) is commonly simplified either by using independence assumptions or dependency models to break down the multivariate PDF to univariate distributions, which are often represented by parametric functions such as Gaussian or Weibull distributions. In the DST case, the multivariate PDF is replaced by a joint basic probability assignment (BPA) with similar simplification possibilities (decomposition into marginal distributions). The uncertainty representation is derived from direct observations such as field data, expert estimates, physical arguments or indirect observations such as similarity information. The process of gathering and building the uncertainty model may be costly." This argues for the use of DST in modeling uncertainty in GPS data.

As Jiang et al. [16] state, evidence theory also has a strong ability to cope with epistemic uncertainty and opens the way to handling dynamic processes with parameters that are (partially) unknown or that depend greatly on environmental influences. However, dealing with a large number of focal elements and the propagation of uncertainty through system models consumes a large amount of time and memory. Jiang et al. developed a reliability analysis method that enables the identification of the most critical focal element–the one that contributes most to failure in the underlying reliability process. This leads to the efficient computation of a reliability interval for the original epistemic uncertainty problem because the computational cost of the structural reliability analysis using evidence theory is determined mainly by the number of focal elements and the search for extreme values of the limit state function for each focal element. In [17], Bai et al. use evidence theory to study the applicability of three important metamodeling techniques for reliability analysis and their overall performance in different test cases, investigating their advantages and disadvantages for predicting low failure probability problems. Our approach was inspired by the construction of a joint BPA structure found in this paper in which multiple variables are involved.

To define imprecise two-dimensional coordinates modeling GPS positions, we extend the DST with univariate distributions by introducing joint interval-valued basic probability assignments (IBPA) with decomposition into marginal distributions. Since the localization is imprecise, intervals are used to model the resulting uncertainty. In order to define and work with these focal elements, we extended the Dempster Shafer with Intervals (DSI) toolbox [18] by adding functions that provide the ability to compute imprecise (GPS) localization, on the basis of two-dimensional and interval-valued basic probability assignments (2DIBPA). The DSI toolbox is derived from Limbourg's IPP toolbox [19] and implements several system functions with uncertain parameters using interval arithmetic and correct rounding; it also proposes a reliable fault tree system model with interval arithmetic (which can be interpreted as a special case of DST) and supports Markov set chains. We use interval computation to describe uncertainty in probability assignments, discretization, and rounding errors. This establishes a workflow for using DST-based models in geographic information system (GIS) application scenarios.

In this paper, we use an approach that employs interval arithmetic and includes controlled rounding; thus, it is fundamentally different from other approaches using stochastic processes, such as Markov chains or Kalman filters. Our approach combines interval arithmetic and stochastic models to compute guaranteed enclosures for a union of focal sets with interval-valued mass distributions. When querying GPS-based data (as is common in GIS applications), the uncertain characteristics of GPS data are seldom