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Design and prototyping of a low-cost vehicle localization system with guaranteed convergence properties

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ABSTRACT

This work presents a low-cost vehicle localization system, using measurements from one gyroscope, two wheel speed sensors and a GPS, to estimate the heading, velocity and position of a vehicle. Taking advantage of the nonholonomic constraints, the design of the observer (or "filter") takes into account imperfections of the embedded sensor measurements, such as a slowly time-varying gyroscope bias or some uncertainty in the wheel diameter value. Thanks to a well-chosen nonlinear structure, the estimator is easy to tune, easy to implement, and well-behaved even at very low speed. Moreover, the proposed filter has guaranteed convergence properties when GPS is available and keeps providing good estimations during GPS losses. Simulation and experiment results in urban area illustrate the good performance of the algorithm.

1. Introduction

The vehicle localization problem has been a field of extensive research over the past 20 years, for military and civil purposes. Recent applications of embedded localization systems, which are able to accurately estimate the vehicle position, velocity, and orientation, involve generating precise urban maps (e.g. Google Streetview, 3D environmental maps from mobile mapping systems), the use of floats of vehicles, such as buses and taxis, to update these maps, and the growing development of semi or fully automatic vehicle control systems. The global position system (GPS) has become a widespread device that is used in most of vehicle localization system (VLS) algorithms. It provides estimations of the vehicle position and velocity in an inertial frame. In normal conditions, standard commercial GPS have a (only) relative accuracy (approximately 2 m circular error of probability in position estimation) and low update rate (1–4 Hz). Moreover, lack of GPS is very common in urban environments (or on country roads surrounded by vegetation). Indeed in the so-called urban canyons, the buildings tend to either mask the GPS transmitted signal, or to reflect it along multipaths, or to gather the visible satellites in a tiny solid angle (increasing estimation errors). Such configurations can lead to excessively degraded GPS signal outputs. Moreover, in indoors environments, or tunnels, GPS is totally unavailable.

For all those reasons, the localization task is generally assigned to embedded sensors which are "aided" by GPS: the sensors drifts are corrected thanks to the GPS estimations, which are, in the long run, accurate on average. Such VLS allow to improve GPS estimations, even in wide-open environments. Recent technological developments of low-cost embedded sensors, especially micro-electro-mechanical systems (MEMS), have been a major factor in the development of such GPS-aided VLS. In addition to GPS, numerous on-board system design have then been proposed: Davidson, Hautamäki, and Collin (2008) and Bevly (2004) use inertial measurement unit (IMU, i.e. accelerometers and gyroscopes), Zhang, Gu, Milios, and Huynh (2005) use IMU and digital compass, Dissanayake, Sukkarieh, Nebot, and Durrant-Whyte (2001) and Di Domenico, Fiengo, and Glielmo (2007) use IMU and speedometers (wheel speed sensors), Hohman, Murdock, Westerfield, Hattox, and Kusterer (2000) use IMU and differential GPS.

The VLS rely then on the fusion of the several sensors measurements and a trusted model of the vehicle dynamics. The trusted dynamical model can be entirely based on general kinematic equations, considering the system as a material point to which a frame is attached (orientation of the vehicle). In this case, any algorithm designed for any moving system (e.g. an aerial vehicle) may be used (e.g. see Martin & Salaün, 2008a, 2008b; Vasconcelos, Silvestre, & Oliveira, 2008; Zhang et al., 2005; or any commercial off-the-shelf system, often called "aided attitude and heading reference systems" (aided AHRS), e.g. MIDG II from Microbotics, or MTi-G from Xsens). However, a specific

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model of terrestrial vehicles may improve the estimation performances. In particular, Dissanayake et al. (2001) have shown that considering nonholonomic constraints significantly improves the precision of the VLS. This kind of roll without slip model has been advocated in several recent publications such as Fiengo, Di Domenico, and Glielmo (2009) and Di Domenico et al. (2007).

The data fusion between the trusted dynamical model, and the several sensors measurements generally relies on standard filtering methods, such as Luenberger observer, Extended or Unscented Kalman Filter (e.g. see Bevly, Ryu, & Gerdes, 2006; Fiengo et al., 2009; Ryu & Gerdes, 2004, or Sebsadji, Glaser, Mammar, & Dakhlallah, 2008 that combines both methods), which yield remarkably good results when properly tuned and implemented. Nevertheless, these techniques suffer several drawbacks: it is not easy to choose the numerous parameters of the filter (the design principally relies on extensive simulations); it is not easy to implement the filter (skills in real-time implementation are required to handle the numerous matrix operations); the filter is computationally expensive and needs an expensive computation board to run the algorithm in real-time.

Another main drawback of the popular filtering techniques is that the models involved are nonlinear, so it is in general very difficult to prove the convergence of the estimation error to zero, even on the first order expansion of the error around any trajectory, since the linearized error equation is time-varying. If the system is badly initialized, or if the estimation differs much from the true state value after a long GPS loss (e.g. in a tunnel), there is absolutely no theoretical guarantee that the filter behaves well, i.e. the estimation error converges to zero. To circumvent this problem, some recent work have aimed at developing nonlinear observers with guaranteed convergence properties (e.g. see Grip et al., 2008; Imsland et al., 2006 who have developed nonlinear observers for lateral velocity estimation using an accurate road friction model, see also Bonnabel, Martin, & Rouchon, 2008, 2009; Lageman, Mahony, & Trumpf, 2008; Lageman, Trumpf, & Mahony, 2010).

In this paper, a low-cost vehicle localization system with guaranteed convergence properties is proposed. It merges measurements from one low-cost gyroscope, two wheel speed sensors and a GPS. Based on the nonholonomic constraints of the vehicle, the observer design takes also into account sensor imperfections such as slowly time-varying gyroscope bias and wheel diameter. Indeed, contrary to high-precision expensive gyroscope that have a very stable in time bias, (that can then be estimated at rest), the bias of low-cost gyroscope is very sensitive to exterior parameters (e.g. temperature) and has a trend to slowly drift. If this bias is not continuously estimated online, it can yield inaccurate estimates of the vehicle state (as shown in Martin & Salaün, 2008b). An online estimation of the gyro bias (and uncertainty in wheel radius value) allows the estimator to provide accurate estimation during relatively long GPS losses.

In addition to its convergence properties, the proposed filtering algorithm is easy to tune (only four parameters to choose), easy to implement and computationally economic (very few scalar operations), with a nice cascade structure; and the gains of the observer automatically adapt to the speed of the car. Last, but not least, no division by terms corresponding to sensors measurements is ever required. Indeed, such division may have a dramatic effect at low speed. One major drawback of usual VLS filtering strategy is the estimation of the yaw angle that is very often based on the *arctan* of the ratio between GPS velocity measurements. As demonstrated in Bevly (2004), this technique leads to very poor results at low speed due to GPS measurements noise: it is then usual to define a threshold in the norm of the velocity (typically 2 m/s) under which the estimated yaw angle is not corrected anymore, see Davidson et al. (2008). The algorithm presented in this paper bypasses this limitation and keeps providing good estimations at very low speed.

To sum up, the main contribution of this article is to propose a simple easy-to-tune nonlinear observer for VLS, which takes into account several sensor measurement imperfections. It can be seen as a credible alternative to Kalman-based filtering algorithms usually used for vehicle localization. Beyond several nice features, the main advantage of the proposed observer is that it has guaranteed convergence properties for a very large set of trajectories (although the system is nonlinear and time-varying). Such theoretical guarantees allow the observer to be robust to GPS losses, and from an industrial viewpoint, it can be of great interest for safety, especially if the estimator is used for feedback control of vehicle.

The structure of the proposed observer is based on the recent theory of "symmetry-preserving observers", introduced in Bonnabel et al. (2008, 2009), which allowed to design nonlinear filters for AHRS and aided AHRS with strong theoretical and practical properties (see Martin & Salaün, 2007, 2010 for AHRS and Martin & Salaün, 2008a, 2008b for aided AHRS). Preliminary theoretical results regarding VLS and symmetry-preserving observers can be found in Guillaume and Rouchon (1998) and Bonnabel et al. (2008).

This paper is organized as follows. In Section 2, the system model is first described, taking into account nonholonomic constraints of the vehicle and imperfections of the low-cost embedded sensors (gyro bias and unknown wheel radius). In Section 3, the convergence properties of the nonlinear estimator are proved. Then, the global estimation strategy and the method to tune the filter parameters are presented in Section 4. Finally, the proposed vehicle localization system is validated through simulation (in Section 5) and experimental results (in Section 6) in urban area: the convergence properties of the estimator and its robustness to low speed and GPS loss are especially highlighted.

2. Physical system

2.1. Motion equations

The Earth is considered flat and defining an inertial frame. The vehicle is supposed to move in a plane. It also assumed that the vehicle velocity vector is always tangent to the trajectory (as in Bonnabel et al., 2008; Dissanayake et al., 2001; Fiengo et al., 2009). In this case, the motion of the vehicle is described by the following nonholonomic equations:

$$\dot{\psi} = \omega,$$

$$\dot{p}^n = \|v\|\cos\psi,$$

$$\dot{p}^e = \|v\|\sin\psi,$$

where ψ is the yaw angle (or heading); ω is the instantaneous angular velocity vector around vertical; $p=(p^n,p^e)$ and $v=(v^n,v^e)=(\dot{p}^n,\dot{p}^e)$ are the position and the velocity vectors of the center of mass with respect to the Earth-fixed frame in North–East coordinates.

2.2. Measurements

Three kinds of sensors are used: one low-cost gyroscope measures $\omega_m = \omega + \omega_b$, where ω_b is a constant vector bias; two wheel speed sensors "measure" the speed of the left and the right wheel (more rigourously, these sensors measure the angular velocity, which is multiplied afterwards by the radius of the wheel to get the speed), resp. u^l and u^r, such that these sensors are