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Nonlinear observer design for GNSS-aided inertial navigation systems with time-delayed GNSS measurements

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ABSTRACT

Global navigation satellite system (GNSS) receivers suffer from an internal time-delay of up to several hundred milliseconds leading to a degeneration of position accuracy in high-dynamic systems. With the increasing interest in GNSS navigation, handling of time-delays will be vital in high accuracy applications with high velocity and fast dynamics. This paper presents a nonlinear observer structure for estimating position, linear velocity, and attitude (PVA) as well as accelerometer and gyro biases, using inertial measurements and time-delayed GNSS measurements. The observer structure consists of four parts; (a) attitude and gyro bias estimation, (b) time-delayed translational motion observer estimating position and linear velocity, (c) input delays for inertial and magnetometer measurements, and (d) a faster than real-time simulator. The delayed PVA and gyro bias estimates are computed using a uniformly semiglobally exponentially stable (USGES) nonlinear observer. The high-rate inertial measurements are delayed and synchronized with the GNSS measurements in the state observer. The fast simulator integrates the inertial measurements from the delayed state estimate to provide a state estimate at current time. The sensor measurements are carefully synchronized and the estimation procedure for the GNSS receiver delay is discussed. Experimental data from a small aircraft are used to validate the results.

1. Introduction

Aiding an inertial navigation system (INS) with position and velocity updates from a Global Navigation Satellite System (GNSS) receiver is widely used for vehicle navigation. The inertial measurement unit (IMU) contributes with high sample rate linear acceleration and angular rate measurements, which are integrated to obtain position, velocity and attitude (PVA) estimates. However, the error builds up quickly resulting in poor accuracy for long-term predictions. The drift is compensated by using low sample rate GNSS measurements. The resulting system is a strapdown INS aided by GNSS measurements where the observer produces high sample rate state estimates.

The integration of inertial and GNSS measurements have traditionally been achieved using Kalman filters (KF) or extended Kalman filters (EKF) for nonlinear systems, see e.g. Grewal, Weill, and Andrews (2007). Within the last decade another approach based on nonlinear observer design for estimating PVA is becoming increasingly popular. The design of nonlinear observers is grounded in systems theory where the stability properties are investigated. Thus the advantage of using nonlinear observers compared to EKFs is a significant reduction in computational load, guaranteed stability properties and reduced need for linearization of the system model. See e.g. Hua (2010); Vik and Fossen (2001), or Grip, Fossen, Johansen, and Saberi (2015) for recent attention of nonlinear observers with significantly stronger stability results than nonlinear KFs. The reduction in computational load when using nonlinear observers compared to nonlinear KFs were investigated in Grip, Fossen, Johansen, and Saberi (2013) and Mahony, Hamel, and Pflimlin (2008), and especially in Johansen, Hansen, and Fossen (2016), where a tightly coupled nonlinear observer was shown to comprise less than 25% of the computational load of a multiplicative EKF (MEKF). The smaller computational footprint allows for a reduction in hardware requirements or increased availability of processing power for other applications. Recent work by Hua et al. (2014); Mahony et al. (2008); Roberts and Tayebi (2011), and Kingston and Beard (2004) as well as Grip, Fossen, Johansen, and Saberi (2012), (2015), use nonlinear observers to estimate PVA, acceleration bias, and gyro bias.

GNSS receivers experience a time delay due to the computational time for position estimation and the data communication time from the receiver to the user. The time delay can be disregarded for low-dynamic applications (e.g. marine vessels and pedestrian use), but it has great

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impact on high-dynamic systems such as high-precision automatic UAV and aircraft landing systems. For high-dynamic applications the sensor measurements should have high sample rate and accurate synchronization to minimize the estimation errors, Skog and Händel (2008). It is therefore important to identify and compensate for sensor time delays.

The work presented here aims to combine a nonlinear attitude observer with accurate position estimation taking the receiver time-delay into consideration. The paper is motivated by the increased interest in highly accurate GNSS applications. Due to the estimation inaccuracies introduced by time-delays in GNSS receivers it is believed time-delay compensation will be mandatory in future GNSS/INS applications with fast dynamics and high velocities.

Estimation in time-delayed systems have been subject to extensive research e.g. Jacovitti and Scarano (1993) who investigated discrete-time systems. Latency determination and compensation are described by Solomon et al. (2011) using an experimental setup. The approach of using Kalman filters for GNSS/IMU systems with time delay have been investigated by Raff and Allgöwer (2006) and Skog and Händel (2011). Time synchronization errors in GNSS/IMU systems are discussed by Skog and Händel (2008). A Kalman filter handling delayed or asynchronous measurements is considered in Blanke (2003, 2006), where the focus is fault tolerant marine operations. Lyapunov functionals are used for stability analysis by Papachristodoulou et al. (2005). Stability of delayed systems is further investigated in Gu and Niculescu (2006) and Albertos and Garcia (2012). Recently, a quad-rotor helicopter application with time delays in the feedback loops was studied by Ailon and Arogeti (2014). In Battilotti (2015) a class of nonlinear predictors for delayed measurements with a known and constant delay is proposed. The nonlinear observer consists of several couples of filters each estimating the state vector at some delayed time instant differing from the previous by a small fraction of the overall delay. By use of a small gain approach Ahmed-Ali, Karafyllis, and Lamnabhi-Lagarrigue (2013) presents a class of global exponential stable nonlinear observers with sampled and delayed measurements, robust towards measurement errors and sampling schedule perturbations. Also, Briat (2014) and Fridman (2014) present extensive research on stability and control of time-delayed systems, and Khosravian et al. (2014, 2015, 2015) propose an observer-predictor approach to delayed GNSS and magnetometer measurements where current position is determined from delayed position estimates. In Siccardi et al. (2016) timing issues in the pulse-per-second signals from GNSS receivers are investigated.

1.1. Contribution of the paper

This paper presents a method for handling time-delayed GNSS measurement in a loosely-coupled strapdown GNSS/INS system. The observer structure is based on a USGES nonlinear PVA estimator, Grip et al. (2013), where the high-rate inertial measurements are delayed to match the delayed GNSS measurements. A fast simulator uses inertial measurements to compensate for the delay in the state estimate. The main contribution is the modification and extension of the nonlinear observer to time-delayed position measurements. The observer makes a correction to the delayed state using the delayed GNSS measurement, which are integrated with delayed INS position estimates. The method can be generally applied to other GNSS/INS integration schemes that employ other state estimation algorithms. The presented approach is tested in a high-dynamic test environment using a small aircraft for experimental validation.

1.2. Organization of the paper

The paper is organized as follows: Section 2 gives an introduction to the experienced time delay in GNSS receivers and how it can be estimated. Section 3 states the delayed navigation problem formally. Section 4 introduces the solution involving the nonlinear attitude estimator, the translational motion observer and the fast simulator. Section 5 presents an alternative implementation of the observer structure, while Section 6 presents simulation results. Section 7 contains experimental results using an unmanned aerial vehicle, while Section 8 gives the concluding remarks.

1.3. Notation and preliminaries

A column vector $x \in \mathbb{R}$ is denoted $x{:=}[x_1; x_2; x_3]$ with transpose $x^\top$ and vector norm $\| x \|_2$. The skew-symmetric matrix of a vector x is given as:

$$S(x){:=}\begin{bmatrix} 0 & -x_3 & x_2 \\ x_3 & 0 & -x_1 \\ -x_2 & x_1 & 0 \end{bmatrix}$$

The attitude can be described with a unit quaternion, $q = [r_q; s_q]$, consisting of a real part, $r_q \in \mathbb{R}$, and a vector part, $s_q \in \mathbb{R}^3$, where $\| q \|_2 = 1$. A vector $x \in \mathbb{R}^3$ can be expressed as a quaternion with zero real part; $\bar{x} = [0; x]$. The product between two quaternions q_1 and q_2 is determined with the Hamiltonian product denoted $q_1 \otimes q_2$.

Several coordinate frames will be utilized in the following where the superscripts e and b will denote the Earth-Centered-Earth-Fixed (ECEF) and the Body-fixed coordinate system, respectively. The local North-East-Down (NED) coordinate system will be denoted n while the Earth-Centered-Inertial frame is given by i. The rotation between two frames can be described using quaternions as, e.g. q_a^c, representing the rotation from generic coordinate frame a to frame c, with a corresponding rotation matrix $R(q_a^c) \in SO(3)$. The rotation of a vector x in the a frame to the c frame is then described as $R(q_a^c)x^a = x^c$ given by $R(q_a^c) = I + 2s_{q_a^c}S(r_{q_a^c}) + 2S(r_{q_a^c})^2$. Rotation rate will be denoted ω_{ac}^d representing the rotation of coordinate system c with respect to a decomposed in d. The Earth rotation rate ω_{ie}^e then describes the rotation of the ECEF frame in inertial frame decomposed in the ECEF frame, where $\omega_{ie}^e = [0, 0, 7.292115 \cdot 10^{-5}] rad/s$.

2. Time delay of GNSS receivers

Using GNSS measurements as aid in inertial navigation systems is widely used. However the inertial sensors commonly have a much (20–500 times) higher sample rate than the GNSS receiver. Accurate time stamping of the measurements in relation to each other is therefore vital in the effort to minimize the error, as falsely time stamped data will introduced errors: if the time of use does not correspond to the time of validity the vehicle might have moved or rotated in the time in-between. If one of the sensors in the aided system experiences a delay the integration precision will suffer as the measurements will not correspond to the correct time stamp.

It is widely known that the GNSS signal can experience delays when travelling from the satellites to the receiver (e.g. multipath, atmospheric delays, and timing errors between satellite and receiver clocks) but as the demand for increased accuracy of navigation solutions is growing, other delays will have to be taken into account as well. In the following the time delay arising between the time of validity of the satellite signals to the data is available to the user is considered. The time delay experienced in the GNSS receiver, stems from the computational time of the position estimation as well as the dissemination of the data from the receiver to the user. The total time delay is hence $\tau = \tau_{cal} + \tau_{dis}$, where the calculation time, τ_{cal}, depends on the number of satellites in the constellation, and the dissemination time, τ_{dis}, covers the time it takes the receiver to output the data to the user, which is directly dependent on the number of bytes to transmit and the communication protocol used. Ideally the position data should be available to the user exactly when the receiver obtains the satellite signals. However, even if the calculation of position could be done