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Long baseline navigation with clock offset estimation and discrete-time measurements

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ABSTRACT

This paper proposes a novel one-way-travel-time long baseline filtering system that includes the estimation of the clocks' offset, which is assumed constant. Considering discrete-time pseudo-range measurements, in addition to the data provided by a Doppler velocity log and an attitude and heading reference system, an augmented system is derived that can be regarded as linear for observability and observer design purposes. Its observability is discussed and a Kalman filter provides the estimation solution, with globally exponentially stable (GES) error dynamics. Simulation results are presented to evaluate the proposed solution, which is also compared with the EKF, including Monte Carlo runs.

1. Introduction

Whether for geo-referencing or control purposes, navigation data is essential for the successful operation of underwater vehicles. The aim of this paper is to provide an alternative methodology for one-way-travel-time (OWTT) long baseline (LBL) navigation with explicit continuous clock offset dynamic estimation.

In underwater applications the global positioning system (GPS) is unavailable due to the strong attenuation that the electromagnetic field suffers in water. As such, alternative positioning methods are required, see Hunt et al. (1974) and Milne (1983) for early references on underwater acoustic positioning systems. LBL navigation is one of the most popular choices when it comes to underwater vehicles, where the two-way-travel-time of acoustic signals from the vehicle to several transponders is usually used for trilateration. In Techy, Morgansen, and Woolsey (2011) three acoustic transponders, with known inertial positions, are considered and an extended Kalman filter (EKF) with a Rauch–Tung–Striebel smoother is implemented to obtain filtered estimates of the states. In Whitcomb, Yoerger, and Singh (1999) a conventional LBL positioning system is combined with a Doppler sonar, with bottom-lock, that includes a magnetometer and roll/pitch sensors, and a complementary low-pass/high-pass filter approach is employed to show that the Doppler precision can be improved. Two different LBL approaches are presented in Vaganay, Bellingham, and Leonard (1998): (i) fix computation approach; and (ii) filtering approach. In the so-called fix computation approach, dead-reckoning is performed between acoustic fixes, which reset the vehicle position whenever available. In the second approach, dead-reckoning is performed but valid travel times are used, whenever available, to correct for dead-reckoning drift. In Kinsey and Whitcomb (2004) preliminary field trials are reported of a navigation system that employs a LBL acoustic positioning system, a Doppler sonar, a fiber-optic North seeking gyro, pressure sensors and magnetic compasses, where the main navigation algorithm resorts to the least-squares method.

A different concept than LBL, where one aims to estimate a segment of the trajectory instead of the current position, is proposed in Jouffroy and Opderbecke (2004), where diffusion-based trajectory observers are considered. In Larsen (2000) the concept of LBL navigation is extended to the case where measurements to a single acoustic source are available, by combining dead-reckoning and rich trajectories to obtain a so-called synthetic long baseline. A similar approach is proposed in LaPointe (2006), where simulations of a so-called virtual long baseline (VLBL) navigation algorithm for autonomous underwater vehicles are presented. The explicit use of single range measurements without trilateration is evaluated in Hegrenas, Gade, Hagen, and Hagen (2009), where the range measurements are fused with the data obtained from an INS in an EKF. Alternative single range solutions can be found, for instance, in Olson, Leonard, and Teller (2006), Webster, Eustice, Singh, and Whitcomb (2009), Gadre and Stilwell (2005), and Batista, Silvestre, and Oliveira (2011). Finally, in terms of acoustic-based navigation methods, it is worth mentioning ultra-short baseline (USBL) acoustic positioning systems, which are rapidly increasing in popularity, see e.g. Peyronnet, Person, and Rybicki (1998), Morgado, Batista, Oliveira, and Silvestre (2011), and references therein. For interesting

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discussions and detailed surveys on underwater vehicle navigation techniques and challenges see Kinsey, Eustice, and Whitcomb (2006), Leonard, Bennett, Smith, and Feder (1998), and Tan, Diamant, Seah, and Waldmeyer (2011), as the literature review provided herein is not exhaustive.

An alternative to two-way-travel-time LBL navigation is OWTT navigation, where synchronous clocks between beacons are assumed available and the time of signal emission is either predefined or encoded and sent through communication modems, see Eustice, Whitcomb, Singh, and Grund (2007), Webster, Eustice, Singh, and Whitcomb (2012), and references therein. However, clock synchronization at the beginning of each mission poses an additional and very heavy burden. Furthermore, clock drift is inevitable in long missions unless synchronization is performed periodically. In previous work by the authors a novel filtering solution was proposed for LBL navigation (Batista, Silvestre, & Oliveira, 2014) based on an extension of the framework for single range measurements detailed in Batista et al. (2011). In these approaches, the range measurements were assumed to be available, either resorting to two-way-travel-time or to OWTT coupled with synchronous clocks and acoustic communications. In short, the system dynamics are augmented, including as system states the range measurements and identifying nonlinear terms with new system states, until the system can be regarded as linear. A careful observability analysis follows and, due to its constructive nature, the Kalman filter provides the estimation solution with globally exponentially stable (GES) error dynamics.

The main contribution of this paper is the development of a novel filtering system for LBL navigation, within a OWTT scheme, that includes the estimation of the unknown offset between the receiver and the emitter clocks, which is assumed to be constant. As a result of the unknown clock offset, instead of ranges one has pseudo-range measurements, which correspond to the true ranges plus an unknown offset. Low rate discrete-time pseudo-range measurements force the filtering error to converge to zero, while higher rate attitude and velocity measurements drive the system dynamics. An augmented system, which can be regarded as linear for observability analysis and observer design purposes, is derived considering the LBL configuration and the introduction of new system states. Its observability is carefully studied and the Kalman filter naturally provides an estimation solution, with GES error dynamics. Previous work by the author on OWTT LBL navigation can be found in Batista (2014), where the novel LBL framework with an OWTT scheme was first described. This paper presents the complete analysis of the system, including observability proofs, as well as the evaluation of the estimation performance, with Monte Carlo runs and a comparison with the EKF. Overall, the simulation results presented herein are also more realistic: slower update rates are considered and clock drift is also incorporated. For the latter, the Kalman filter parameters are tunned such that a slowly time-varying clock offset can be successfully tracked. Previous works applying state augmentation to applications with LBL positioning can be found in Leonard and Rikoski (2001), Rikoski (2003), and Stanway (2012), where past measurements were included in the state. In the present work the differences between pseudo-ranges are considered as additional states.

Another possible source of error in OWTT LBL navigation is the sound speed profile. That specific problem has been addressed by the author, in a two-way-travel-time setting, in Batista (2013). Addressing both issues, i.e., determining the sound speed and the clock offset in a OWTT setting, is out of the scope of this paper. In underwater acoustic navigation multipath is also a common problem. While that is also out of the scope of the paper, there exist many algorithms in the literature to handle the presence of outliers, see e.g. Olson et al. (2006) and Yoerger, Jakuba, Bradley, and Bingham (2007).

The problem statement and the nominal system dynamics are introduced in Section 2, while the filter design is detailed in Section 3. Simulation results are presented in Section 4, and Section 5 summarizes the main results of the paper.

1.1. Notation

Throughout the paper the symbol $\mathbf{0}$ denotes a matrix of zeros and $\mathbf{I}$ an identity matrix, both of appropriate dimensions. A block diagonal matrix is represented by $\text{diag}(\mathbf{A}_1, \ldots, \mathbf{A}_n)$. For $\mathbf{x} \in \mathbb{R}^3$ and $\mathbf{y} \in \mathbb{R}^3$, $\mathbf{x} \cdot \mathbf{y}$ represents the inner product.

2. Problem statement

Consider a LBL acoustic positioning system, consisting of a set of emitters that are fixed in the mission scenario, where an underwater vehicle operates, which is equipped with an acoustic receiver, as depicted in Fig. 1. The inertial positions of the emitters, which are constant, are assumed to be available to the vehicle. In an OWTT setting, the fixed beacons, which are assumed to have their clocks synchronized, emit a signal, tagged with the senders' time or at a predefined broadcast time, which is then received by the acoustic receiver that is installed on-board the agent. Typically, the clock of the receiver is also synchronized with that of the receivers and the distance is computed from the time-of-flight and the sound speed profile. In this paper, the offset between the emitting and receiving clocks is assumed to be an unknown constant, and as such instead of range measurements one has pseudo-range measurements, which are measured periodically. Further suppose that the vehicle is equipped with an attitude and heading reference system (AHRS) and a Doppler velocity log (DVL). The problem considered herein is that of designing a continuous-discrete filter, with globally exponentially stable error dynamics, to estimate the position and the linear velocity of the vehicle, as well as the offset between the emitting and receiving clocks.

2.1. System dynamics

Let $\{I\}$ denote a local inertial reference coordinate frame and $\{B\}$ a coordinate frame attached to the vehicle, usually referred to as the body-fixed reference frame. An example of a local inertial frame is the North-East-Down (NED) frame. Although this is not an inertial frame due to the rotation of the Earth, it can be assumed as such for applications as in this paper. Then, the linear motion of the vehicle is described by

$$\dot{\mathbf{p}}(t) = \mathbf{R}(t)\mathbf{v}(t), \tag{1}$$

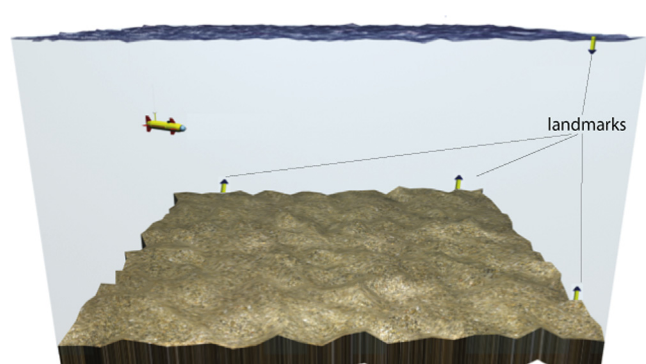

Fig. 1. Long baseline mission scenario.