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Globally exponentially stable filters for underwater position estimation using an array of hydroacoustic transducers on the vehicle and a single transponder

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ABSTRACT

This paper presents two novel globally exponentially stable position estimators using hydroacoustic measurements from a single transponder to several transceivers on the vehicle. A comparison study of these and several existing filters is conducted with both experimental and simulated data. Two classes of filters for position estimation are compared: filters expressing the position of an underwater vehicle in the body-fixed and north-east-down coordinate frames. The comparison study showed that the latter formulation yields lower estimation errors. Furthermore, one of the novel filters developed in this paper using the north-east-down formulation is found to serve well as a compromise between performance, theoretical stability, and computational complexity relative to the near-optimal linearization-based filters with which it is compared.

1. Introduction

Current subsea inspection, maintenance, and repair (IMR) operations are heavily dependent on manually operated remotely operated vehicles (ROVs). This is time-consuming and expensive as it requires deployment of a surface vessel and experienced personnel, Schjølberg et al. (2016). Increased autonomy in current ROV operations may make current operations more efficient, while being a stepping-stone towards future solution that e.g. are independent of the expensive surface vessel. This paper considers inertial navigation of an (UV) in areas of little interest, e.g. in transit between subsea facilities.

Inertial navigation of an underwater vehicle (UV) commonly involves two steps. One is the integration of rate measurements in order to update position and attitude estimates. These measurements are often provided by accelerometers or Doppler velocity log (DVL) for position estimation and angular rate sensor (ARS) for attitude estimation. Due to the noisy and biased nature of inertial measurements, the integration causes the position and attitude estimates to drift over time. Therefore, a second step is needed, namely aiding the inertial navigation using absolute measurements of position and attitude. The absolute measurement for attitude estimation is often provided by on-board sensors such as accelerometers and magnetometers or compasses. These provide body-fixed measurements of known reference vectors in the global frame, and from this, the rotation between the body-fixed and global frame can be calculated. For underwater position estimation, these absolute measurements often come from hydroacoustic networks providing range measurements from known locations. Most commonly used is the long baseline (LBL) network in which several transducers are mounted on the sea-bed and one transducer is carried by the vehicle. The short baseline (SBL) has a similar structure, except the array of transducers are mounted under a surface vessel, from which the UV with one transducer is often employed. In ultrashort baseline (USBL) systems, the array of transducers are compactly fitted inside an apparatus that is mounted under a surface vessel. The baselines, i.e. the geometry of transducers, impact the position estimation accuracy, where longer distances and more diversity generally yield higher estimation accuracy. For an overview of these set ups, we refer to Vickery (1998). These acoustic set ups also exist in slightly modified configurations. The GPS intelligent buoy (GIB) network is similar to LBL, only that the transducers are mounted to global positioning system (GPS) positioned buoys. In inverted ultrashort baseline (iUSBL), the USBL apparatus is mounted on the UV. Lastly, Stovner and Johansen (2017) suggested an inverted short baseline (iSBL) set up in which transducers are spaced out as widely as possible on the UV. This gives a similar set up as the iUSBL, but the baselines are now confined to the size of the UV instead of a small apparatus. This set up is depicted in Fig. 1.

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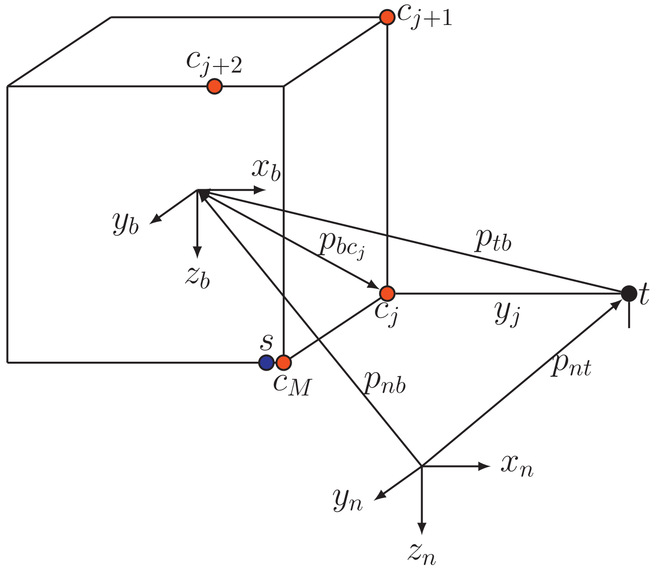

Fig. 1. The iSBL set up with a sender s (blue) and receivers c_j (red) mounted on an UV, and a transponder t on the seabed (black). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

The advantage of both iSBL and iUSBL compared to e.g. LBL is the lower requirement for external infrastructure. Assuming an attitude estimate is available, iSBL and iUSBL only needs contact with one transponder in order to find its global position, whereas with LBL, three transponders are typically needed. In areas of little interest, e.g. in transit between subsea facilities, it is desirable to install as little infrastructure as possible, both to save deployment and maintenance costs. The trade-off of navigation precision for less infrastructure is not critical in these areas.

Due to longer baselines, iSBL is potentially more accurate than iUSBL. Also, one can use cheap light-weight transducer elements instead of a relatively expensive, heavy, and large USBL apparatus. This is especially important for small light-weight UVs. Morgado et al. (2011a, b); Batista et al. (2014) developed Kalman filters (KFs) with global stability properties using a linear model achieved through state augmentation for iUSBL measurements. There, the range and range-difference measurements were used in a tightly-coupled scheme, and not used to calculate a position measurement or range and bearing measurements as is common with USBL sensors. Also, the receiver baselines on the vehicle are larger than one would typically expect from a USBL apparatus, i.e. they spanned $20 \times 30 \times 30 cm$. Therefore, the proposed hydroacoustic set up in Morgado et al. (2011a) has many similarities with the measurement set up used in this paper. Morgado et al. (2013) presented an extended Kalman filter (EKF)-based solution for the same measurement set up, where the full state, i.e. position, velocity, and attitude along with ARS and accelerometer biases, was estimated.

Another set up that requires only one transponder exists, in which only one transceiver on the vehicle is assumed as well. This estimation problem is not observable in each instant, but can be shown to be observable over time for sufficiently rich vehicle movements, as shown by Batista et al. (2010) for a state augmentation based solution to the nonlinear estimation problem. Several EKF- and particle filter (PF)-based solutions have also been developed, see e.g. Ferreira et al. (2010); Saúde and Aguiar (2009).

The EKF is the workhorse for estimation of nonlinear systems. It linearizes the nonlinear model about its own estimate, and employs the linearized model in a linear KF. However, the feedback of the state estimate as a linearization point is potentially destabilizing. This has inspired solutions where a linear model is achieved without the need for the feedback of the state estimate. Batista et al. (2012) and Morgado et al. (2011a) find a linear model by algebraic manipulation of the measurement equations, thus avoiding the feedback of a linearization point. Furthermore, they are able to show global stability properties. Another way of linearizing the nonlinear model while avoiding the feedback of a linearization point is to linearize about an exogenous state estimate which has desired stability properties, but may be suboptimal. This is the idea of the exogenous Kalman filter (XKF) of Johansen and Fossen (2017). A special case of the XKF is the three-stage filter (3SF) of Johansen et al. (2016) where the linearization point is provided by a cascade of an algebraic transformation that supplies a linear model to a suboptimal but globally asymptotically stable KF. The algebraic transformation stage is generally similar to that in Bancroft (1985) and Chaffee and Abel (1994). Stovner et al. (2016) developed a 3SF for underwater position estimation using an LBL network, which Jørgensen et al. (2016) improved upon by a more accurate model of the noise. In Stovner et al. (2017) the 3SF was used for body-fixed position estimation with an iSBL network, and Stovner and Johansen (2017) extended the work to aid attitude estimation in the case of unreliable magnetometer measurements.

The presented work contains several contributions. The 3SFs of Stovner et al. (2017) are improved upon by using a novel algebraic transformation inspired by Morgado et al. (2011a). The novel algebraic transformation produces a linear time-varying (LTV) measurement model where the original range and range difference measurements are still used as measurements. This is contrary to Batista et al. (2012), where a position was calculated and used as measurement; Morgado et al. (2011a, b) and Batista et al. (2014), where state augmentation was used to handle nonlinear terms; and Stovner et al. (2017), where the algebraic transformation constructed new measurements that drastically increased the effect of measurement noise. The novel filters, which essentially are improvements on those of Stovner et al. (2017), express the state both in the body-fixed and northeast-down (NED) coordinate frames. These are thoroughly developed and shown to have global exponential stability (GES) error dynamics.

The filters are compared both in simulations and experimentally to Stovner et al. (2017), a loosely coupled filter, and a standard EKF implementation. The second stage LTV KFs using the NED formulation is shown to outperform the second stage filters of Stovner et al. (2017). In fact, it is shown to yield nearly as good performance as the third stage filter based on the linearized model. Therefore, with a minor reduction in estimation precision, one can reduce the computational burden by half relative to the 3SF presented in Stovner et al. (2017).

The contributions are summarized below:

- Two novel three-stage filter for underwater position estimation are developed and proven to have global exponential stability error dynamics. This comes with robustness guarantees, especially with regards to the transient behavior.
- The filters are verified in simulations and experiments, and calculated mean absolute error values show that EKF-like performance is achieved.

2. Preliminaries

On the UV, there is one transmitting and M receiving hydroacoustic transducer elements denoted the *sender* and *receivers*, respectively. In the vehicle's surroundings, a *transponder* is placed, capable of both receiving and transmitting. This set up is depicted in Fig. 1.

Let p^a_{bc} denote the position of point c relative to point b decomposed in the coordinate frame a. In the case where c or b generally denote a coordinate frame, the point is the origin of the respective frame. Now, $p^b_{bc_j}$ and p^b_{tb} denotes the position of receiver c_j relative to the vehicle and the vehicle relative the transponder t, respectively, both decomposed in the body-fixed frame. p^n_{nb} and p^n_{nt} denotes the position of the vehicle and transponder relative to the origin of the local NED frame, respectively, both decomposed in the NED frame. Similarly, the ground velocity of the