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Hybrid Observer Combining Measurements of Different Fidelities ⋆

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Abstract: A signal-based hybrid observer combining measurements of different fidelities is proposed for position and velocity estimation of marine vessels. The concept assumes that noisy position measurements are available only sporadically at a non-constant sampling rate. Predictions of position between the samples are provided by integrating acceleration measurements, which are available at a high rate (approximated to be continuous sampling). Estimates with smaller variance are computed by averaging multiple observer copies of the position. This work is a continuation of the observer proposed in Brodtkorb et al. (2015). The main contributions of this paper is extending the observer to the more realistic scenario where linear velocity and angular acceleration measurements are not available. A simulation study showed that the observer performed well in closed loop with a controller conducting dynamic positioning operations of a marine vessel.

Keywords: Observers, hybrid systems, dynamic positioning, sensor fusion

1. INTRODUCTION

Observers are important components of dynamic positioning (DP) systems for marine vessels. Common observer types used in DP today include model-based designs such as the nonlinear passive observer (NPO), see Fossen and Strand (1999), or an exteded Kalman filter, see Sørensen (2011) for an overview and the references therein. For other examples of implementation in DP see for instance Tannuri and Morishita (2006) and Hassani et al. (2013). These observers are based on a kinetic model of the vessel, and use position measurements from e.g. Global Navigation and Sensor Systems (GNSS), hydro-acoustic, laser, or microwaves, to reconstruct unmeasured states, filter out wave frequency motions, estimate bias, and in case of signal loss, do dead reckoning.

Signal-based, or kinematic, observers are also recently proposed for DP applications. These do not contain model parameters nor vessel-specific information, in contrast to model-based observers. In general, the methods integrate acceleration and angular rate measurements from inertial measurement units (IMU) to compute position and attitude estimates, correcting the estimates from drifting using position and compass (or magnetometer) measurements. Gravity and gyro bias are also compensated. For details see e.g. Grip et al. (2012), Grip et al. (2015) and Bryne et al. (2015).

The observers mentioned here assume in the design that the measurements are available continuously, which is not the case in reality. This was addressed in Brodtkorb et al. (2015), where measurements of position, velocity and acceleration were fused in a hybrid signal-based observer. The observer design was based on the assumption that position and velocity measurements were available only sporadically, and used acceleration measurement available at a high rate for position prediction. On a similar note, Ferrante et al. (2016) considers state estimation of linear systems where the measurements are available sporadically. The work considers systems where data used for control is transmitted over networks, where data can get lost or is available intermittently.

This paper extends the observer from Brodtkorb et al. (2015) to the more realistic case where no linear velocity and angular acceleration measurements are available. The observer error dynamics are shown uniformly globally asymptotically stable (UGAS) by using theory from hybrid dynamical systems as described in Goebel et al. (2012) and cascaded systems. The observer is tested in simulations of a marine surface vessel conducting DP operations.

The paper is organized as follows: Section 2 introduces the mathematical model and available measurements used for the observer design. The observer is designed in Section 3, and stability is discussed in Section 4. The observer is

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tested in simulations of a surface vessel in DP in Section 5, and Section 6 concludes the paper.

2. MATHEMATICAL MODELING

Two reference frames are used thoughout this paper. The North-East-Down (NED) frame is a local Earth-fixed reference frame with origin at the mean free surface, and the second reference frame is a body-fixed frame. The NED frame is assumed inertial.

2.1 Marine Vessel Modeling

The signal-based observer is based on the kinematic (strapdown) equations relating position, velocity and acceleration of the vessel. Here, we are looking only at motions in the horizontal plane, so we only consider surge, sway and yaw motions [1]. The equations of motion are

$$\dot{p} = R(\psi)v \tag{1a}$$
$$\dot{\psi} = r \tag{1b}$$
$$\dot{v} = a \tag{1c}$$

where p is the position vector in north and east, v is the body-fixed surge and sway velocity vector, a is the body-fixed surge and sway acceleration vector, ψ is the heading angle, and r is the yaw rate. Throughout this paper the rotation matrix $R(\psi)$ refers to the 2×2 rotation matrix given by

$$R(\psi) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) \\ \sin(\psi) & \cos(\psi) \end{bmatrix}. \tag{2}$$

2.2 Measurements

DP vessels have statutory class requirements on the onboard instrumentation, and system redundancy. Vessels have positioning systems, e.g. GNSS, acoustics, or laser, a compass measuring heading angle, and inertial measurement units (IMU) that combine gyroscopes for measuring angular rates and accelerometers for measuring linear acceleration. The measurements are taken at different sampling rates ranging from 0.1-2 Hz for acoustics, 0.5-4 Hz for GNSS position measurements, to 100-200 Hz for IMU angular velocity and acceleration measurements.

We assume to have measurements of position $p = [N\ E]^\top$ and heading ψ with non-constant sample time in the interval $[T_{min}, T_{max}]$, where $0 < T_{min} \leq T_{max}$. The yaw rate r, and linear acceleration a are assumed to be measured at a high rate, approximated as continuous sampling. We also assume that r and a are bounded. Notice that we do not have linear velocity or angular acceleration measurements available. Noise on the measurements is not considered in the stability analysis, but is included in the simulations.

For convenience we constrain the system states to a compact set $\mathcal{K}$, $(p, \psi, v) \in \mathcal{K} \subset \mathbb{R}^5$. The observer design does not depend on this set.

[1] Since we are considering only surge, sway and yaw motion, the coupling effects in roll and pitch are neglected, as well as the effect of gravity.

3. HYBRID OBSERVER

A hybrid observer is designed based on (1) by utilizing the measurements when they are available. The observer states, denoted $(\cdot)_i$, flow with the yaw rate and linear acceleration measurements, and are updated with the occasional position and heading measurements. To mitigate the effect of position and compass measurement noise, multiple copies of position, heading and velocity are saved in the observer and averaged. The position, heading, and velocity estimates are

$$\hat{p} := \frac{1}{N}\sum_{i=1}^{N} p_i, \quad \hat{\psi} := \frac{1}{N}\sum_{i=1}^{N} \psi_i, \quad \hat{v} \quad := \frac{1}{N}\sum_{i=1}^{N} v_i \tag{3}$$

where $p_i,\ i = \{1, ..., N\}$ are the north and east position states in the observer, ψ_i are the heading states, and v_i are the linear velocity states. The observer states flow as

$$\dot{p}_i = R(\hat{\psi})v_i \tag{4a}$$
$$\dot{\psi}_i = r \tag{4b}$$
$$\dot{v}_i = a \tag{4c}$$
$$\dot{M} = R(\hat{\psi}) \tag{4d}$$
$$\dot{\tau} = -1, \tag{4e}$$

with $i = \{1, ..., N\}$ copies of position, heading and velocity flow with the available yaw rate r and acceleration measurement a. The states are allowed to flow when

$$\begin{aligned} &((p, \psi, v), (p_1, \psi_1, v_1), ..., (p_N, \psi_N, v_N), M, \tau) \in C \\ &C := \mathcal{K} \times (\mathbb{R}^2 \times \mathbb{R}^1 \times \mathbb{R}^2)^N \\ &\quad \times \left\{P \in \mathbb{R}^{2\times 2} : ||P||_2 \leq T_{max}\right\} \times [0, T_{max}]. \end{aligned} \tag{5}$$

In particular M belongs to the set of 2×2 matrices with induced 2 norm less than or equal to T_{max}, see Section 4.3 for details. The observer flows in between position and compass measurement times, when $\tau \in [0, T_{max}]$. A new position and compass measurement is available with non-constant sampling time with at least T_{min} seconds between samples and at most T_{max} seconds. Hence a jump is triggered when $\tau = 0$, with the jump dynamics

$$p_i^+ = p_{i-1} \tag{6a}$$
$$\psi_i^+ = \psi_{i-1} \tag{6b}$$
$$v_i^+ = v_i + \kappa M^{-1}(p_i - p_{i-1}), \tag{6c}$$
$$M^+ = 0, \tag{6d}$$
$$\tau^+ \in [T_{min}, T_{max}], \tag{6e}$$

with $i = \{1, .., N\}$ and the measurements $p_0 := p$ and $\psi_0 := \psi$. The measurements of position and heading are saved into the first observer states (p_1, ψ_1), and the remainder of the states are shifted one place back in the shift register. The velocity states are updated with the state itself, and a correction term consisting of a gain κ, the inverse of the matrix M involving the rotation matrix integrated over time, and the error between position states i and $i-1$. The jump set is

$$\begin{aligned} &((p, \psi, v), (p_1, \psi_1, v_1), ..., (p_N, \psi_N, v_N), M, \tau) \in D \\ &D := \mathcal{K} \times (\mathbb{R}^2 \times \mathbb{R}^1 \times \mathbb{R}^2)^N \\ &\quad \times \left\{P \in \mathbb{R}^{2\times 2} : ||P||_2 \leq T_{max},\ \det(P) \geq \rho\right\} \times \{0\}. \end{aligned} \tag{7}$$

The observer has two parameters; κ in (6c), which can be anything in $(-2, 0)$, and $\rho > 0$ in (7) which ensures that $\det(M)$ is larger than zero so that M is invertible during jumps. This last constraint is related to making sure that