A Global Exponential Observer for Velocity-Aided Attitude Estimation

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Outline

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MOTIVATION

- Attitude estimation is crucial for control purposes
- Estimation algorithms are required to be robust and performant in the presence of uncertainties and perturbations
- For lightweight, low-cost systems equipped with a MEMS Inertial Measurement Unit, "true" inertial navigation (i.e., based on the Schuler effect due to a rotating non-flat Earth) is excluded due to limited accuracy in the long run
- Inertial sensors must be "aided" by incorporating
  - a model of the forces acting on the vehicle, in which case the estimator is specific to the vehicle
  - an additional sensor, providing information in inertia or body axes (Sun tracker, Doppler radar, camera); in this case the estimator can be generic, but at the cost of the extra sensor

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Motivation

Existing works

- Almost globally asymptotically converging solutions available
- Design/stability on the natural geometry $\mathbb{SO}(3) \times \mathbb{R}^3$ more involved ([Hua,Martin,Hamel AUT2016],[Mahony,Hamel TAC2008])
- Known gravity direction
- Global decoupling of pitch and roll estimation from magnetic measurements

Proposed solution

- Globally exponentially converging estimate
- Simple Design/stability established on $\mathbb{R}^3 \times \mathbb{R}^3 \times \mathbb{R}^3$
- Gravity direction estimated
- Global decoupling of pitch and roll estimation from magnetic measurements

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Outline

Kinematic models

Attitude kinematics

We consider a moving rigid body subjected to the angular velocity ω (in body axes). Its orientation (from inertial to body axes) matrix $R \in \mathrm{SO}(3)$ is related to ω by

$$\dot{R} = RS(\omega), \tag{1}$$

where $S(\omega)$ is the skew-symmetric matrix defined by $S(\omega)x := \omega \times x$ whatever the vector x.

Reduced attitude kinematics

Define as gE_3 the gravity vector (in Earth axes). The dynamics of the gravity vector (in body axes) $\gamma := gR^T E_3$ is then

$$\dot{\gamma} = \gamma \times \omega \tag{2}$$

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MEASUREMENTS

- $v_m = v$ – Linear velocity in body frame
- $\omega_m = \omega$ – Angular velocity in body frame
- $a_m = a$ – Specific acceleration
- $\beta_m = \beta$ – Magnetic field in body frame
- $y := \texttt{col}(v_m, \beta_m), \qquad u := \texttt{col}(a_m, \omega_m)$

REMARK

If B is the known constant magnetic field vector (in Earth axes), $\beta := R^T B$ and

$$\dot{\beta} = \beta \times \omega \tag{3}$$

Measurements' model

Measurements

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Remark

If B is the known constant magnetic field vector (in Earth axes), $\beta := R^T B$ and

$$\dot{\beta} = \beta \times \omega \tag{3}$$

Measurements' model (cont'd)

Dynamical model

$$
\begin{aligned}
\dot{v}_m &= v_m \times \omega + \gamma + a_m && (4)\\
\dot{\beta}_m &= \beta_m \times \omega_m && (5)
\end{aligned}
$$

Approach for attitude estimation

For $B \times E_3 \neq 0$, R is completely specified by γ and β since

$$
\begin{aligned}
R^T &= R^T \begin{pmatrix} gE_3 & B & gE_3 \times B \end{pmatrix} \cdot \begin{pmatrix} gE_3 & B & gE_3 \times B \end{pmatrix}^{-1}\\
&= \begin{pmatrix} \gamma & \beta & \gamma \times \beta \end{pmatrix} \cdot \begin{pmatrix} gE_3 & B & gE_3 \times B \end{pmatrix}^{-1}, && (6)
\end{aligned}
$$

with $R^T(x \times y) = R^T x \times R^T y \ \forall x, y$.

DYNAMICAL MODEL

$$\begin{aligned} \dot{v}_m &= v_m \times \omega + \gamma + a_m && (4) \\ \dot{\beta}_m &= \beta_m \times \omega_m && (5) \end{aligned}$$

APPROACH FOR ATTITUDE ESTIMATION

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with $R^T(x \times y) = R^T x \times R^T y \; \forall x, y$.

Complete model

Model for estimator design

$$
\begin{aligned}
\dot{v}_m &= v_m \times \omega_m + \gamma + a_m && (7)\\
\dot{\gamma} &= \gamma \times \omega_m && (8)\\
\dot{\beta}_m &= \beta_m \times \omega_m. && (9)
\end{aligned}
$$

Notice the two subsystems (7)-(8) and (9) are completely independent.

Measurements

$y := \mathtt{col}(v, m)$, $\qquad u := \mathtt{col}(a, \omega)$

OUTLINE

Observer design

Observer

$$\dot{\hat{v}} = \hat{v} \times \omega_m + a_m + \hat{\gamma} - (L + K)(\hat{v} - v_m) \quad (10)$$
$$\dot{\hat{\gamma}} = \hat{\gamma} \times \omega_m - \big(LS(\omega_m) - S(\omega_m)L + LK\big)(\hat{v} - v_m) \quad (11)$$
$$\dot{\hat{\beta}} = \hat{\beta} \times \omega_m - M(\hat{\beta} - \beta_m), \quad (12)$$

where the 3×3 matrices K, L, M are tuning parameters. The observer is a copy of (7)–(9) with (time-varying) correction terms, which respects the decoupled structure of (7)–(9).

$\hat{\gamma}$ is independent of magnetic measurements

If R is parametrized by the Euler angles (ϕ, θ, ψ), γ reads

$$\gamma = g\begin{pmatrix} -\sin\theta & \sin\phi\cos\theta & \cos\phi\cos\theta \end{pmatrix}^T$$

γ thus encodes the roll and pitch angles, which are crucial for stabilization purposes (whereas the yaw angle matters far less).

Observer design

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Error dynamics (perfect measurements)

- Error variables

$$\begin{aligned} e_v &:= \hat{v} - v \\ e_\gamma &:= \hat{\gamma} - \gamma - L e_v \\ e_\beta &:= \hat{\beta} - \beta \end{aligned}$$

- Error dynamics

$$\begin{aligned} \dot{e}_v &= e_v \times \omega + e_\gamma - K e_v & (13) \\ \dot{e}_\gamma &= e_\gamma \times \omega - L e_\gamma & (14) \\ \dot{e}_\beta &= e_\beta \times \omega - M e_\beta & (15) \end{aligned}$$

Theorem

If the symmetric parts of K, L, M are positive definite, then the equilibrium point $(\bar{e}_v, \bar{e}_\gamma, \bar{e}_\beta) := (0, 0, 0)$ of the error system (13)–(15) is globally exponentially stable.

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Observer design

Proof sketch – Lyapunov function

$$V(e_\gamma, e_v, e_\beta) \quad := \quad \underbrace{\frac{\rho_1}{2}\left|e_\gamma\right|^2 + \frac{\rho_1\epsilon^2}{2}\left|e_v\right|^2}_{=:V_\gamma(e_\gamma, e_v)} + \underbrace{\frac{1}{2}\left|e_\beta\right|^2}_{=:V_\beta(e_\beta)}, \quad \rho_1, \epsilon > 0$$

$$\begin{aligned} \dot{V}_\beta &= -\langle e_\beta, \frac{M + M^T}{2} e_\beta \rangle \leq -\underline{\sigma}_M \left|e_\beta\right|^2 \\ \dot{V}_\gamma &\leq -\rho_1\left(\underline{\sigma}_L - \frac{\epsilon}{2}\right)\left|e_\gamma\right|^2 - \rho_1\epsilon^2\left(\underline{\sigma}_K - \frac{\epsilon}{2}\right)\left|e_v\right|^2, \end{aligned}$$

with $\underline{\sigma}_M$ the smallest eigenvalue of $\frac{M+M^T}{2}$.

PROOF SKETCH (CONT'D) – ROTATION MATRIX ESTIMATE

Under the assumptions of Theorem 1,

$$\tilde{R} \quad := \quad \begin{pmatrix} \frac{(\hat{\gamma}\times\hat{\beta})\times\hat{\gamma}}{|(gE_3\times B)\times gE_3|} & \frac{\hat{\gamma}\times\hat{\beta}}{|gE_3\times B|} & \frac{\hat{\gamma}}{|gE_3|} \end{pmatrix}^T$$

globally exponentially converges to the orientation matrix R.

Best orthogonal approximation

Proposition

Considerer the polar decomposition of $\tilde{R}^T$

$$\tilde{R}^T = \hat{R}^T(\tilde{R}\tilde{R}^T)^{\frac{1}{2}}.$$

Then $\hat{R}$, which is by construction the best approximation of $\tilde{R}$ among all orthogonal matrices, is a rotation matrix that globally exponentially converges to R. When $\hat{\gamma}$ and $\hat{\beta}$ are not collinear, $\hat{R}$ is uniquely defined by

$$\hat{R} := \begin{pmatrix} \frac{(\hat{\gamma}\times\hat{\beta})\times\hat{\gamma}}{\left|(\hat{\gamma}\times\hat{\beta})\times\hat{\gamma}\right|} & \frac{\hat{\gamma}\times\hat{\beta}}{\left|\hat{\gamma}\times\hat{\beta}\right|} & \frac{\hat{\gamma}}{|\hat{\gamma}|} \end{pmatrix}^T.$$

Local tuning

Linear Time-Varying error dynamics

Rotated error coordinates: $(E_v, E_\gamma, E_\beta) := (Re_v, Re_\gamma, Re_\beta)$

$$\dot{E}_v = E_\gamma - RKR^T E_v \tag{16}$$
$$\dot{E}_\gamma = -RLR^T E_\gamma \tag{17}$$
$$\dot{E}_\beta = -RMR^T E_\beta, \tag{18}$$

$(K, L, M) := (kI, lI, mI)$– Time-Invariant dynamics

$$\dot{E}_v = E_\gamma - kE_v \tag{19}$$
$$\dot{E}_\gamma = -lE_\gamma \tag{20}$$
$$\dot{E}_\beta = -mE_\beta; \tag{21}$$

For different gains on the components of each correction term, as for instance when the velocity sensor has for technological reasons a "privileged" direction (in general the vertical axis).

$$K := \begin{pmatrix} k_x & -k_y & 0 \\ k_y & k_x & 0 \\ 0 & 0 & k_z \end{pmatrix} \quad L := \begin{pmatrix} l_x & -l_y & 0 \\ l_y & l_x & 0 \\ 0 & 0 & l_z \end{pmatrix},$$

with $k_x, k_z, l_x, l_z > 0$; K (resp. L) has a pair of complex conjugate eigenvalues when $k_y \neq 0$ (resp. $l_y \neq 0$). For a trajectory of the system such that

$$R := \begin{pmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

where ψ arbitrary function of time; $RKR^T = K$ and $RLR^T = L$.

$$\begin{aligned} \dot{E}_v &= E_\gamma - KE_v \\ \dot{E}_\gamma &= -LE_\gamma \end{aligned}$$

OUTLINE

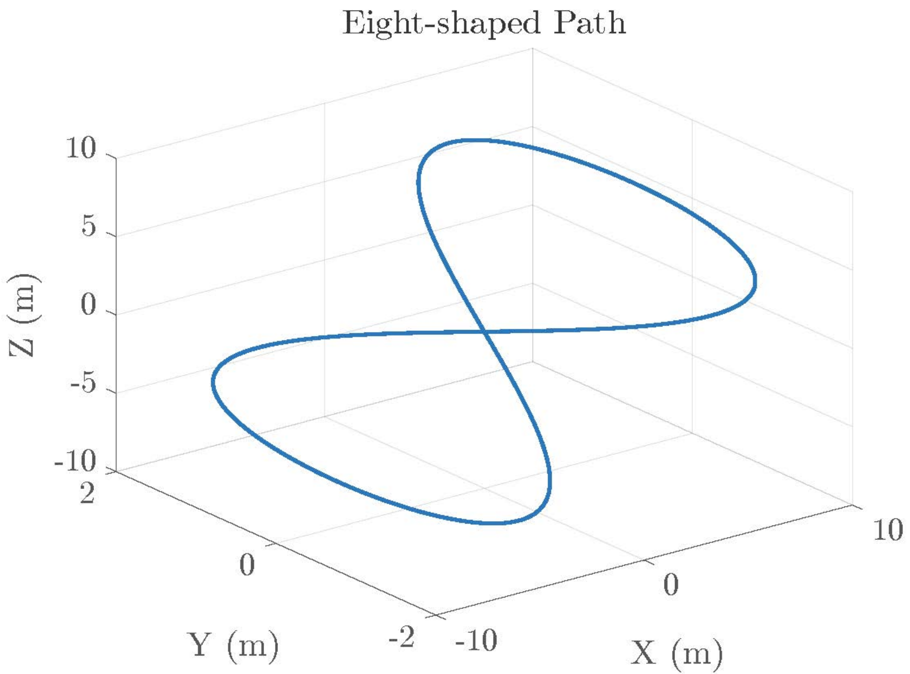
SIMULATIONS

SCENARIO

- Aggresive trajectory
- Robustness wrt corrupted measurements
- Observer initialized with no error, but suddenly reinitialized at $t = 50$
- Magnetic vector B set to the nominal value $(1/\sqrt{2}, 0, 1/\sqrt{2})^T$, but subjected to a violent disturbance for $t \in [80, 100]$

GAINS

$(K, L, M) := (5I, 5I, 0.5I)$

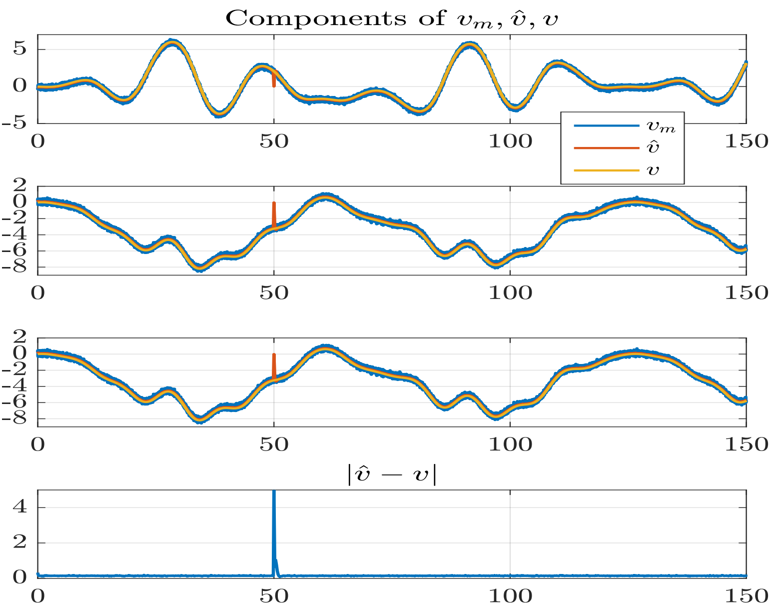

Eight-shaped Path
Z (m)
10
5
0
-5
-10
Y (m)
2
0
-2
X (m)
-10
0
10

CORRUPTED MEASUREMENTS

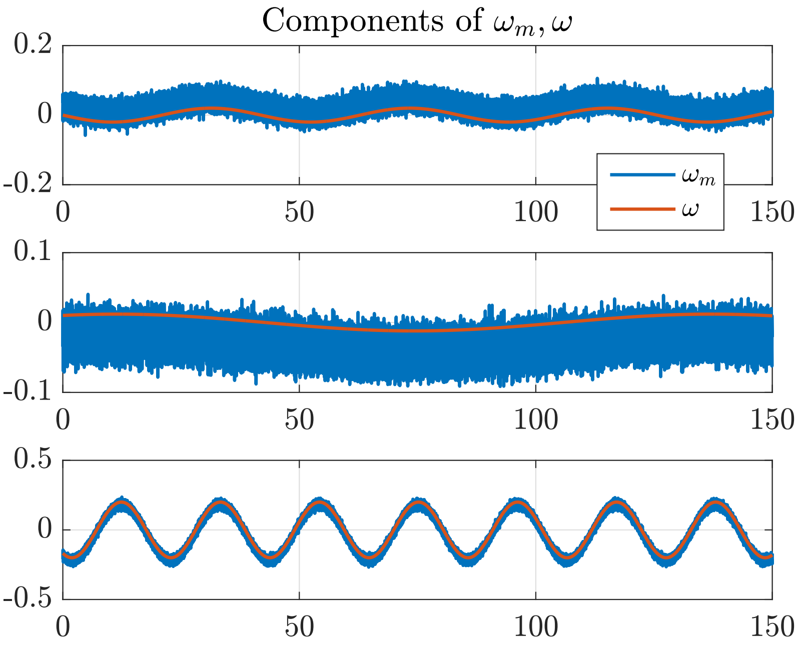
$$
\begin{aligned}
v_m &= v + b_v + \nu_v && (22)\\
\omega_m &= \omega + b_\omega + \nu_\omega && (23)\\
a_m &= a + b_a + \nu_a && (24)\\
\beta_m &= \beta + b_\beta + \nu_\beta, && (25)
\end{aligned}
$$

b_v	$(-0.10\ 0.30\ \ -0.05)^T$	σ_v^2	$10^{-5}(2\ 2\ 2)^T$
b_ω	$(0.0250\ \ -0.0300\ \ -0.0175)^T$	σ_ω^2	$10^{-7}(2\ 2\ 2)^T$
b_a	$(0.05\ 0.04\ \ -0.02)^T$	σ_a^2	$10^{-5}(1\ 1\ 1)^T$
b_β	$(0.024 - 0.020 - 0.018)^T$	σ_β^2	$10^{-5}(1\ 1\ 1)^T$

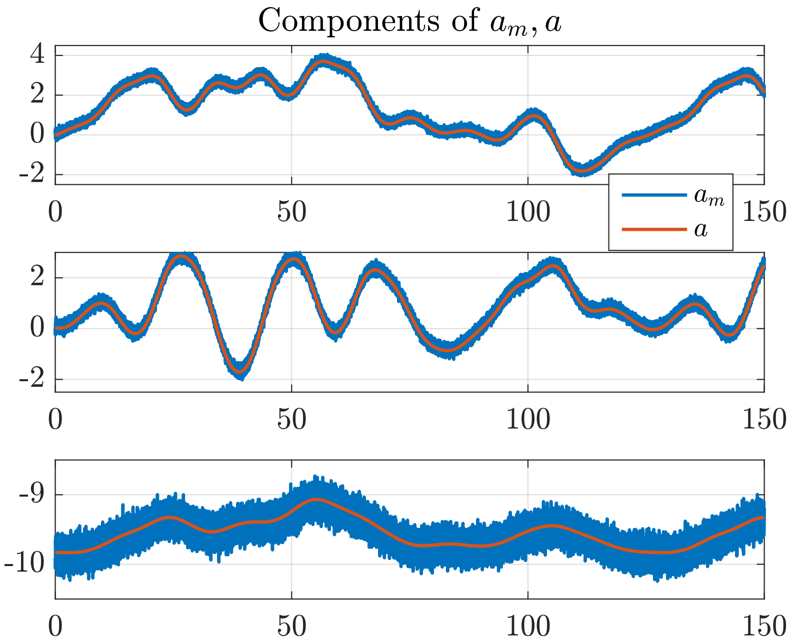
TABLE: (Constant) Biases and (white Gaussian independent noises with intensities σ_i)noises in the actual measurements.



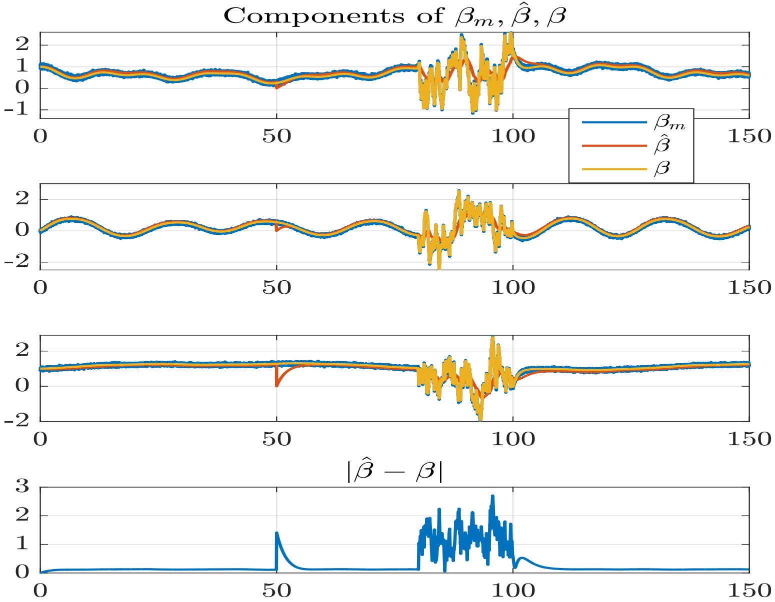
Components of $v_m, \hat{v}, v$
v_m
$\hat{v}$
v
5
0
-5
2
0
-2
-4
-6
-8
$|\hat{v} - v|$
4
2
0
0
50
100
150



Components of ω_m, ω
0.2
0
-0.2
0
50
100
150
ω_m
ω
0.1
0
-0.1
0
50
100
150
0.5
0
-0.5
0
50
100
150

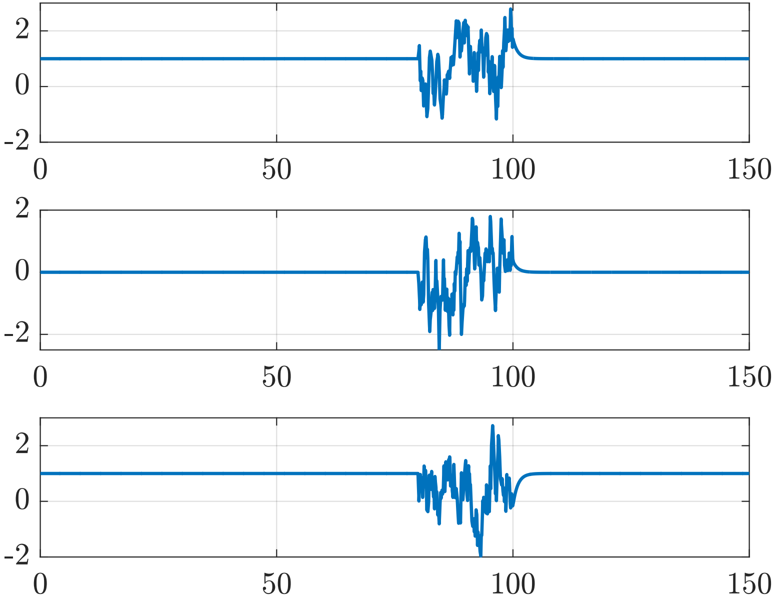


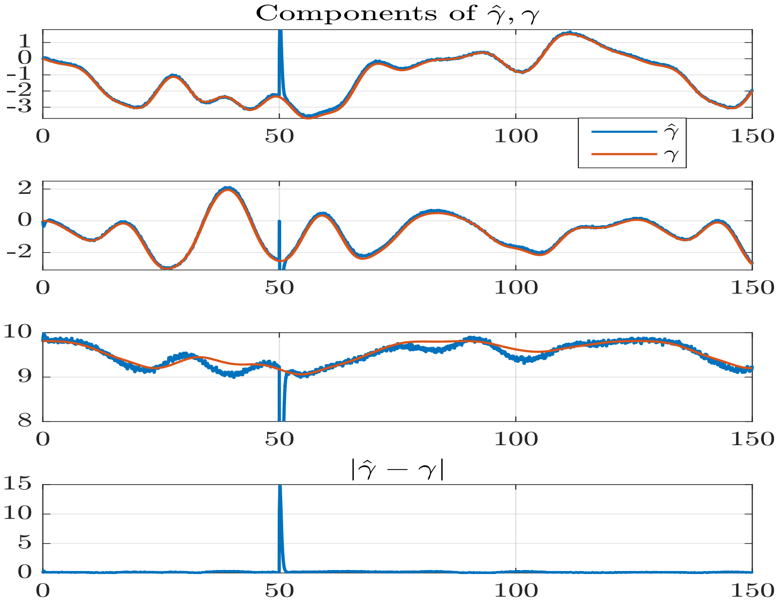
Components of a_m, a
4
2
0
-2
0
50
100
150
a_m
a
2
0
-2
0
50
100
150
-9
-10
0
50
100
150

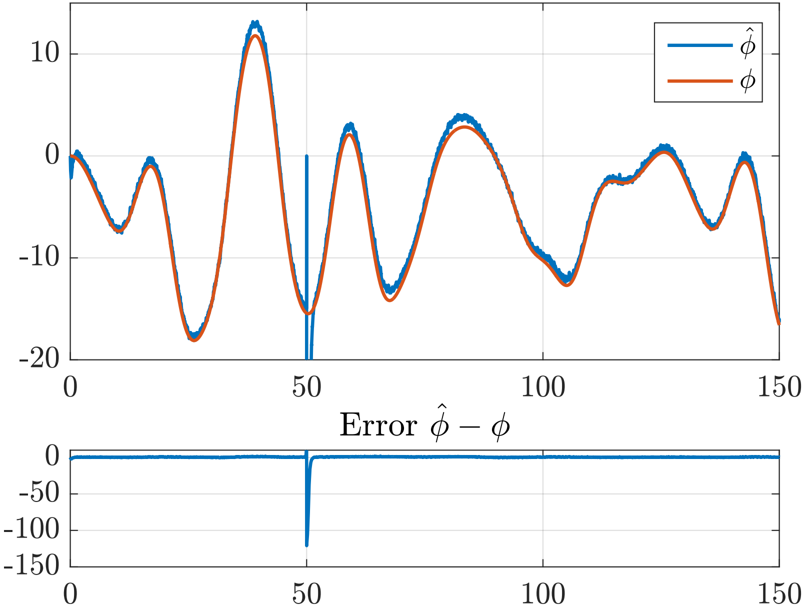


Components of $\beta_m, \hat{\beta}, \beta$
β_m
$\hat{\beta}$
β
$|\hat{\beta} - \beta|$

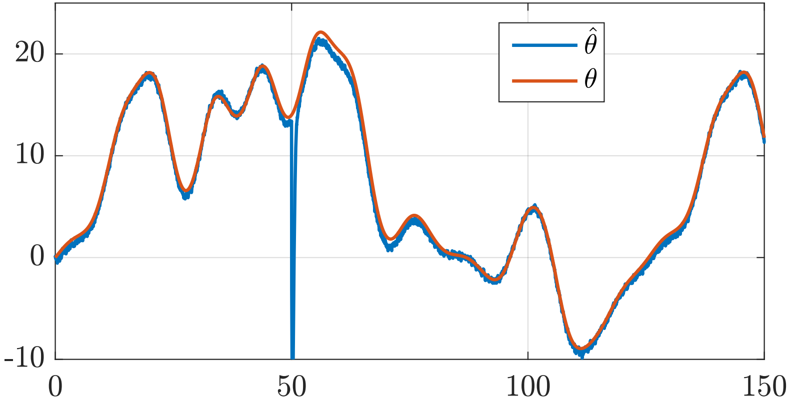
Components of B



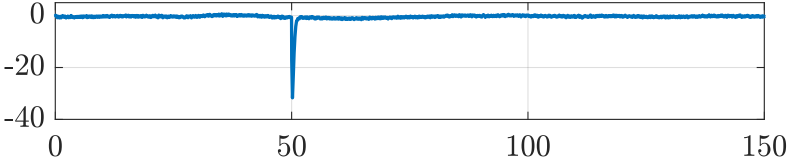

Components of $\hat{\gamma}, \gamma$
$\hat{\gamma}$
γ
$|\hat{\gamma} - \gamma|$

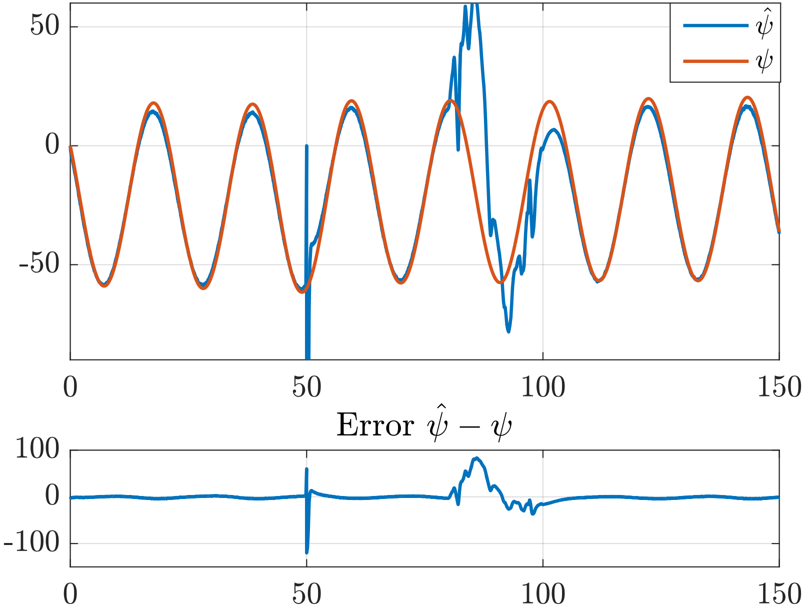


$\hat{\phi}$
ϕ
10
0
-10
-20
0
50
100
150
Error $\hat{\phi} - \phi$
0
-50
-100
-150
0
50
100
150



Error $\hat{\theta} - \theta$





50
0
-50
0
50
100
150
$\hat{\psi}$
ψ
Error $\hat{\psi} - \psi$
100
0
-100
0
50
100
150

Outline

Conclusions-Extensions

Conclusions

- (Velocity,Magnetic field,Gyro)-measurement scenario for global attitude estimation
- Model parameterization => Linear Time-Varying dynamics with constraints
- Observer derived using the invariant-manifold–based approach ([Astolfi,Karagiannis,Ortega])
- Observer = Copy of system + (Linear/Nonlinear) Correction terms
- Constant tuning gains
- Global exponential convergence – Robustness wrt small perturbations
- Good observer performance in the presence of unaccounted bias and (additive) disturbances

EXTENSIONS

- Inertial velocity measurement instead of body velocity
- Account for gyro bias
- Account for vector bias
- Time-delay in measurements
- Experimental validation

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- P. Martin and I. Sarras, "A simple global observer for attitude and gyro biases", *IFAC World Congress*, 2016, submitted. (version arXiv available)