Graybox Modeling of Ships Using Indirect Input Measurements

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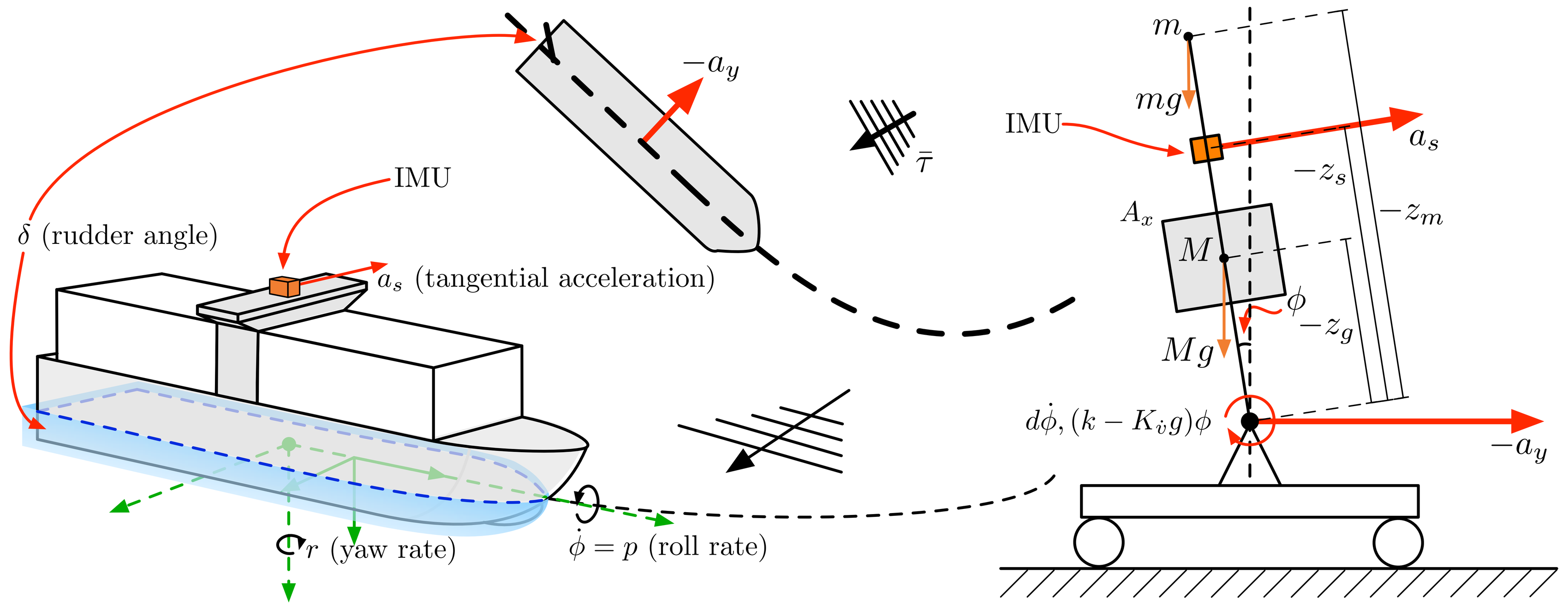
The Generalized Model



The model is derived from a well-established nonlinear ship model

$$\bar{\boldsymbol{M}}(\vartheta_p)\dot{x} = F(x, \delta, \vartheta_p) + T\bar{\tau} \tag{1}$$

After linearization and a few manipulations, the fourth component is

$$\begin{aligned} A_1\ddot\phi &= -(k + Mgz_g + mgz_m)\phi - d\dot\phi \\ &\quad + (K_{\dot v} + Mz_g + mz_m)\dot v + (K_{ur} + Mz_g + mz_m)Ur + K_\delta\delta + \tau \end{aligned} \tag{2}$$

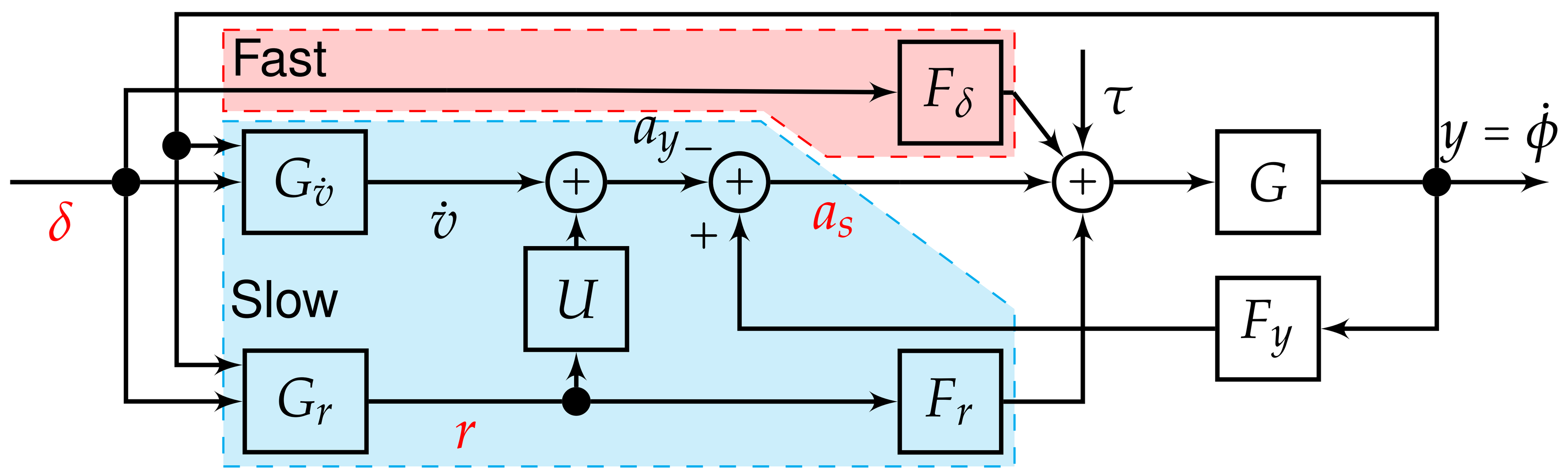
where $A_1 = A_x + Mz_g^2 + mz_m^2$. The motion of the ship is measured using an inertial measurement unit (IMU). The measurement is $[\dot\phi,\ r,\ a_s]^T + e$ where the tangential acceleration is given by

$$a_s = z_s\ddot\phi + g\phi - a_y = z_s\ddot\phi + g\phi - \dot v - Ur \tag{3}$$

Equation (2) and (3) can be combined and give after a few manipulations

$$\begin{aligned} A_2\ddot\phi &= -(k - K_{\dot v} g)\phi - d\dot\phi \\ &\quad - (K_{\dot v} + Mz_g + mz_m)a_s + K_r r + K_\delta\delta + \tau \end{aligned} \tag{4}$$

where $A_2 = A_x + Mz_g(z_g - z_s) + mz_m(z_m - z_s) - K_{\dot v} z_s$. To show how the signals relate to each other, the models can be drawn in a block diagram



which reveals additional information.

The proposed method solves the unknown acceleration problem, however, it introduces some new challenges.

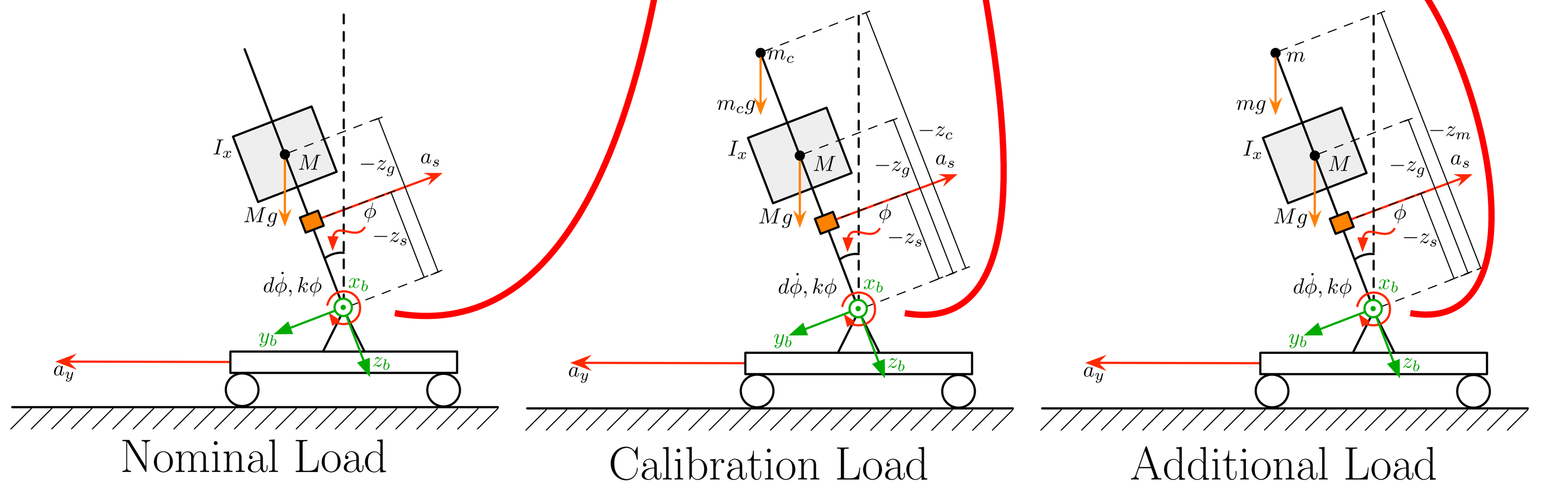
1. The signals r, a_s and y are all **correlated** with the disturbance τ.
2. The loop gain from τ to a_s has a **direct term**.
3. Since the true r, a_s and y are not known but measured, the input will be noisy, i.e. this is an **errors-in-variables** problem.

The Joint Graybox Method

Due to identifiability issues, *a priori* information and multiple datasets have to be used to estimate the unknown parameters.

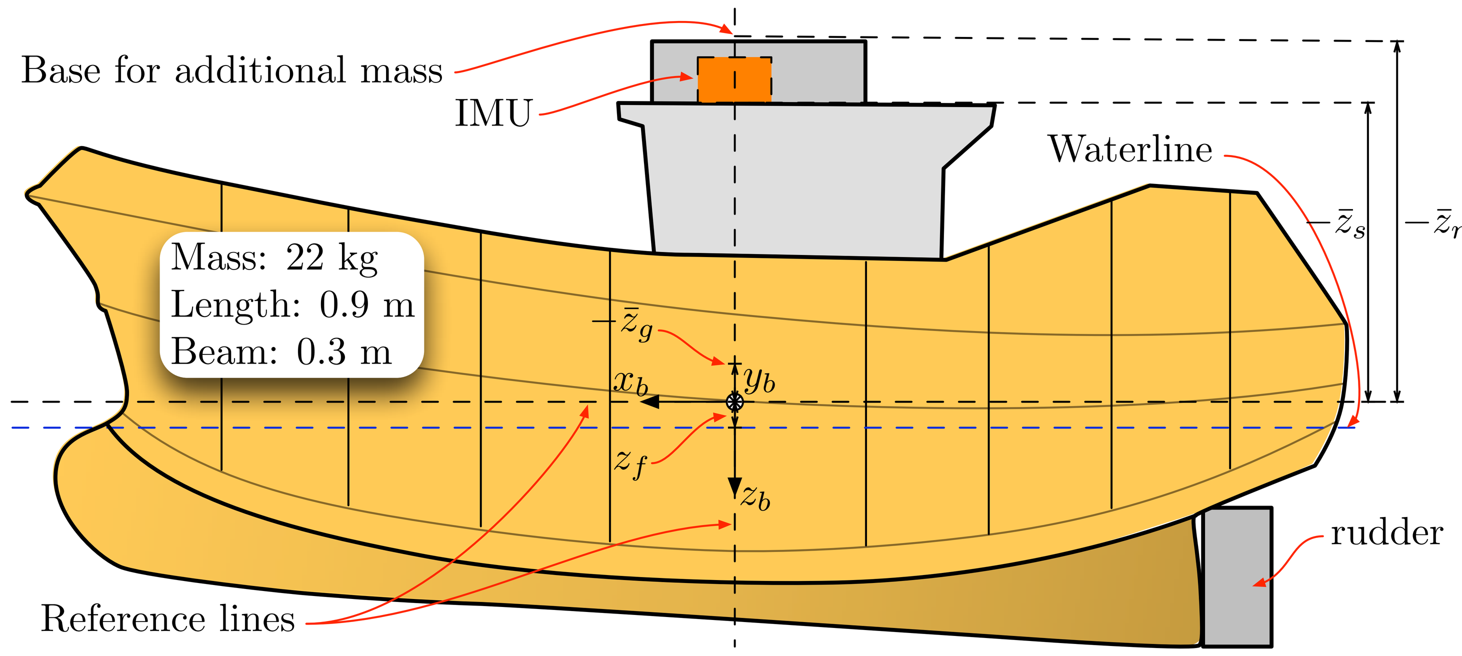
$$\tilde\vartheta_p = [\overbrace{\underbrace{M,\ \bar z_g,\ m_c,\ \bar z_c}_{\tilde\vartheta_{p,1}}}^{\tilde\vartheta_{p,1}},\ \overbrace{\underbrace{k,\ A_x,\ d}_{\tilde\vartheta_{p,2}},\ \underbrace{m,\ \bar z_m}_{\tilde\vartheta_{p,3}},\ \underbrace{K_r,\ K_{\dot v},\ K_\delta,\ z_f}_{\tilde\vartheta_{\text{hydrodynamic}}}}^{\tilde\vartheta_{p,2}}]^T$$

a priori — Joint Estimation

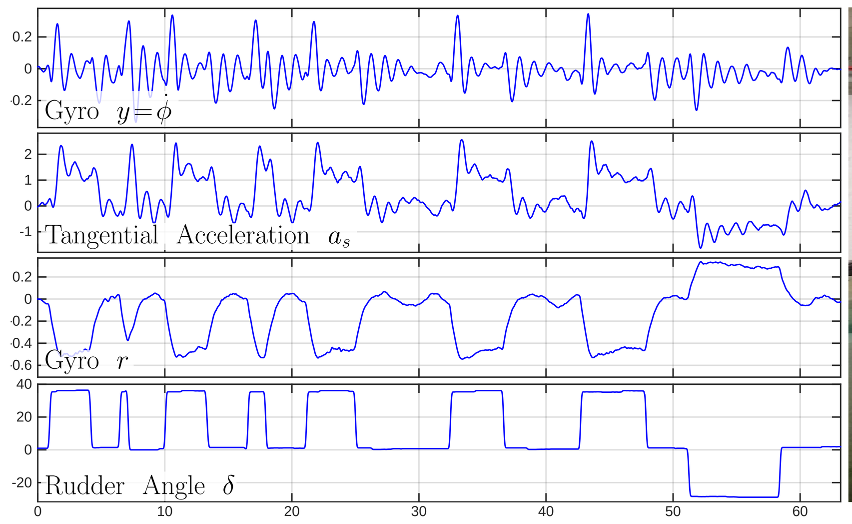


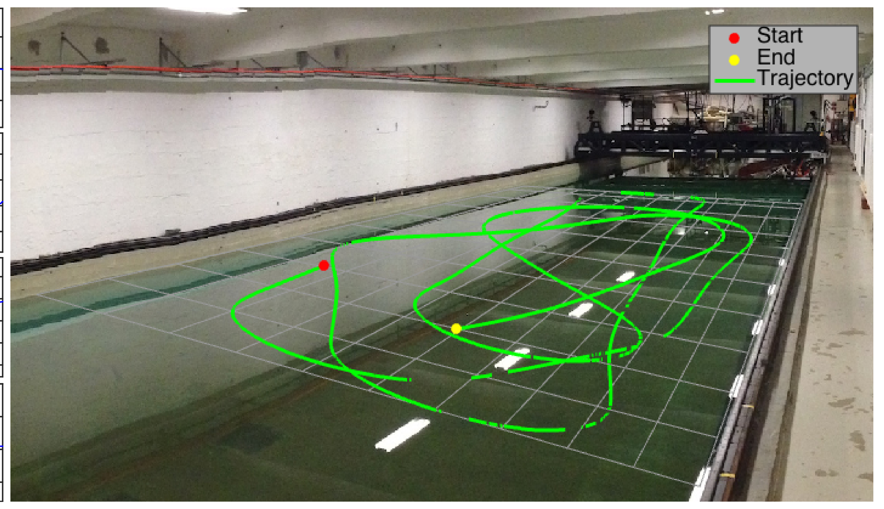
Note that the nominal and calibration datasets can be collected once and are only used as a basis for comparison. Data can then be collected during **normal operational conditions** to estimate the change in mass and change in center of mass. A graybox formulation is used since the datasets are related through the physical parameters.

Experiment Setup and Data



An experiment was carried out in a model basin. The experiments were performed using a scale model of a fishing vessel in scale 1:24. The scale model had its own propulsion and rudder, and was operated in free run experiments where it was controlled using a joystick. The nominal dataset that was used in the next section can be seen below.





Results

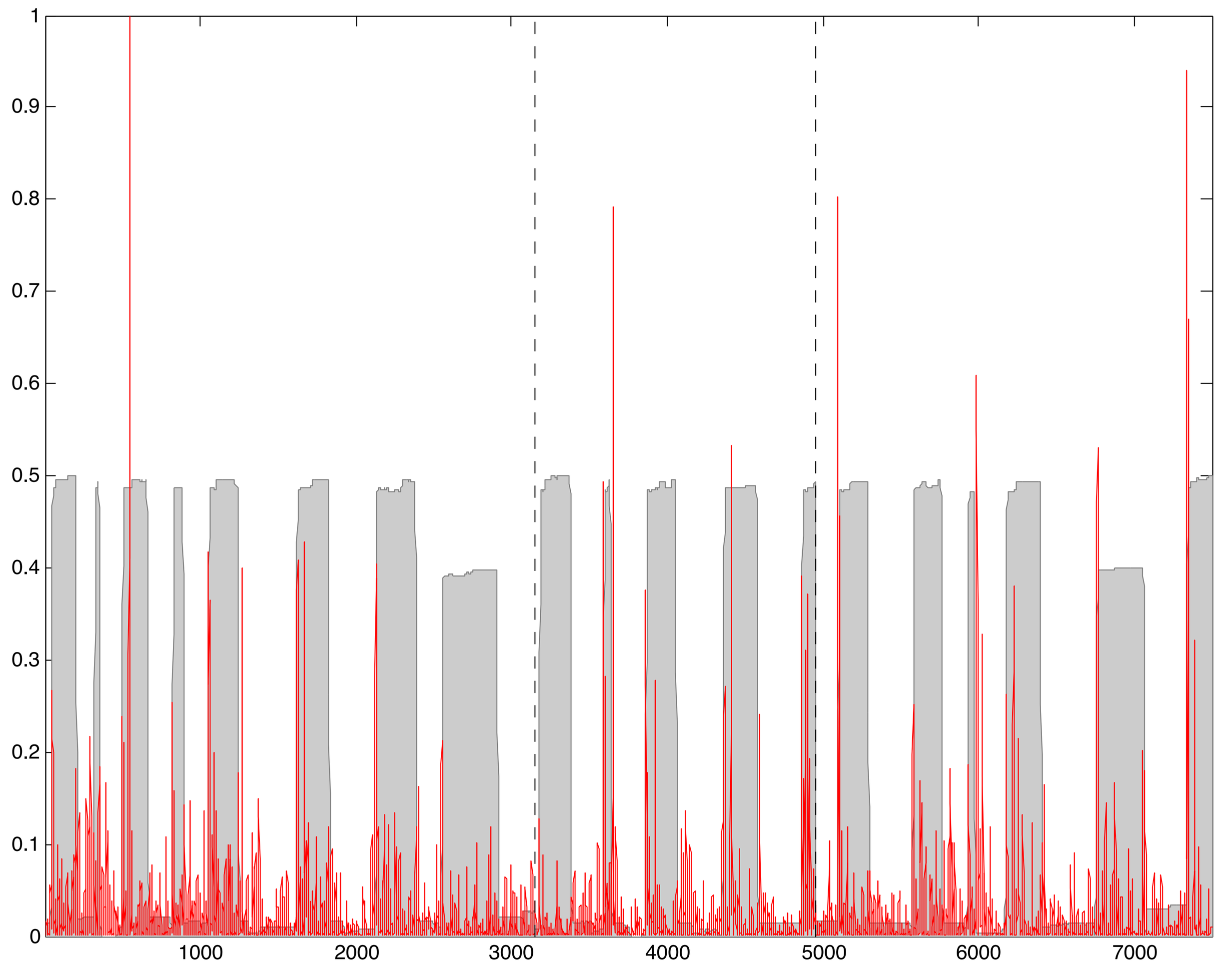
Several datasets were collected for different loading conditions and four of these were used to produced the results. The datasets were combined into three cases as seen in the table below.

Case	Nominal Dataset	Calibration Dataset	Loaded Dataset
1	Nominal – 1	0.200 kg – 2	0.200 kg – 3
2	Nominal – 1	0.200 kg – 3	0.400 kg – 4
3	Nominal – 1	0.200 kg – 2	0.400 kg – 4

The datasets were chosen since they were similar to each other, for example, having the same maximum rudder angle and similar lengths, and since there were no strong nonlinear effects visible in the data.

The results for each case can be seen below. The first case shows the best results which is excepted since it has the most similar loaded and calibration datasets. The largest relative error, 16.6 %, corresponds to 66.5 gram error in the mass estimation which is 0.3 % of the total mass.

	A_x	d	k	K_δ	K_r	$K_{\dot v}$	z_f	m	$\bar z_m$
1	0.1583	0.2685	9.0057	−0.4822	−2.0100	0.9607	−0.0294	0.1997	−0.2529
	–	–	–	–	–	–	–	0.134%	1.21%
2	0.1566	0.2668	9.0067	−0.4433	−1.9911	0.9408	−0.0293	0.3690	−0.2426
	–	–	–	–	–	–	–	7.75%	9.48%
3	0.1571	0.2675	9.0021	−0.4383	−1.9995	0.9516	−0.0294	0.3335	−0.2671
	–	–	–	–	–	–	–	16.6%	0.329%



Right, the normalized residuals (red) of Case 1 are plotted together with the scaled absolute value of the rudder angle (gray). It can be seen that there is a clear correlation between the large spikes and the turn entries. This indicated that there was unmodeled dynamics and this might have made a variance calculation misleading due to the deterministic components in the residuals.

Future Work

- Robustification
- Extending the model to deal with nonlinear behavior
- Further investigations of data

Core Problems

- Indirect input measurements
- Graybox formulation for data fusion
- The subsystem viewpoint and the properties of the resulting estimators