Unmanned Water Craft Identification and Adaptive Control in Low-Speed and Reversing Regions

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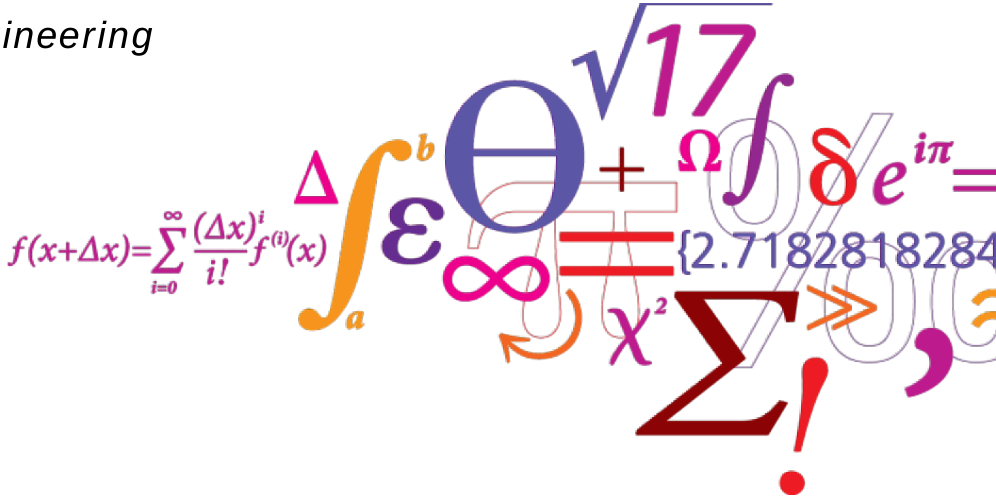


Presentation overview

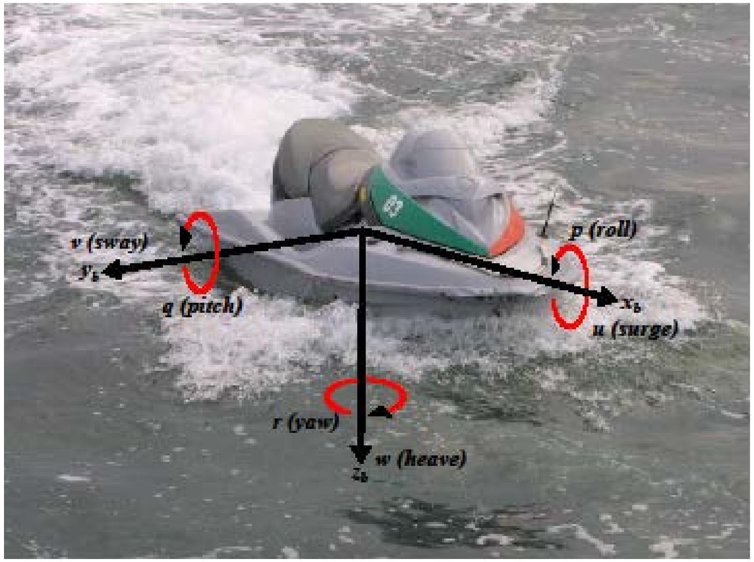
- Motivation
- Modeling of Personal Water jet craft (PWC) from sea trial data
- Baseline PD controller with non-adaptive wave filter and L1 adaptive augmentation
- Robustness analysis
- Results

Motivation

- Personal Water jet crafts (PWCs)
  - Capable of fast agile manoeuvring
  - Suitable for complex autonomous missions
  - Requires station-keeping
  - Challenge due to under-actuation

- No model available
  - Identification from sea trials
  - Found parameters are uncertain
  - Calls for robust control

    -> L1 adaptive heading control
- Proposed L1 adaptive controller
  - Adapts to uncertain parameters
  - While limiting the control actuation response to HF wave induced motion.

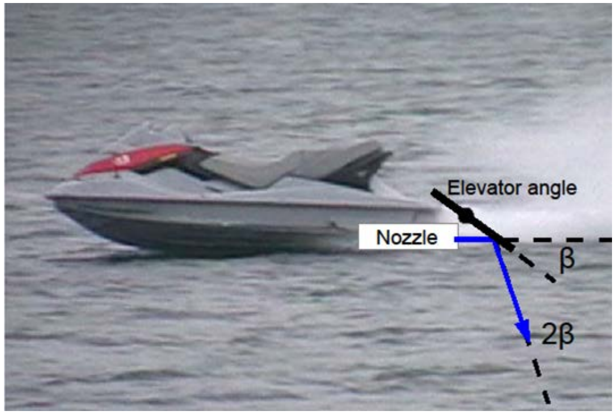


The PWC at sea and body frame coordinate system

Modeling of Water Jet Vehicle

- Modelling from full scale sea trial data sets
- Control inputs

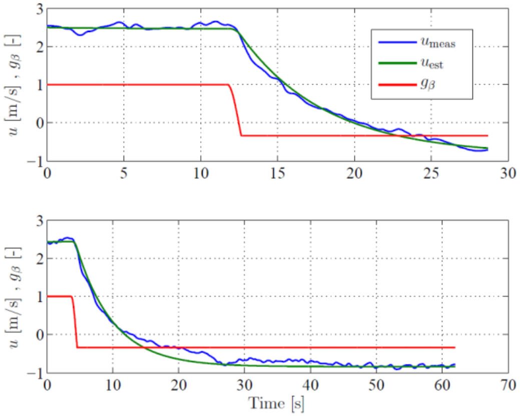
– Thrust	T	Jet thrust
– Azimuth	δ	Horiz. jet direction
– Elevator deflection	β	Vert. jet direction

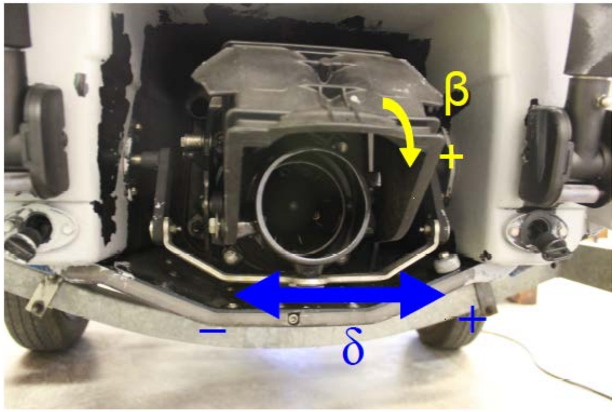


The elevator modeling of the PWC

Experiments

- Surge identification from elevator steps

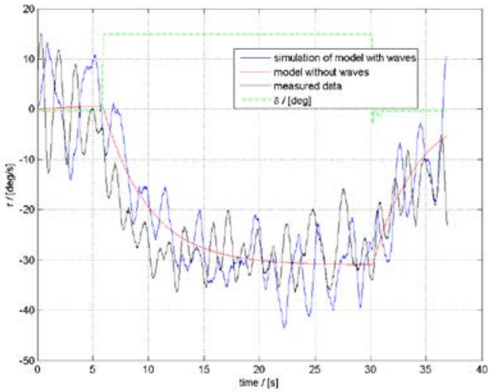


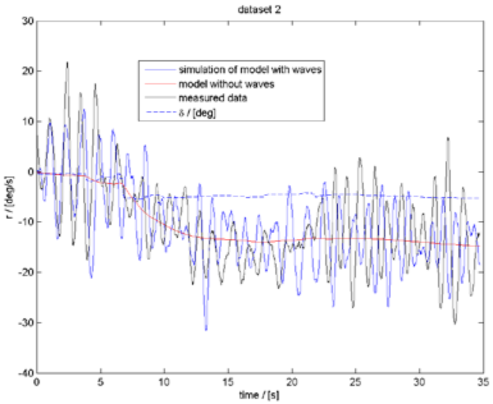


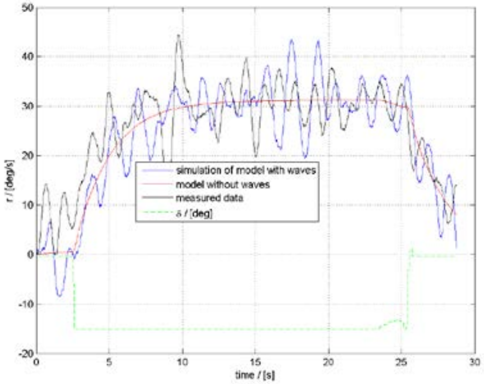
The nozzle. Deflection β of the blade controls vertical direction of water jet

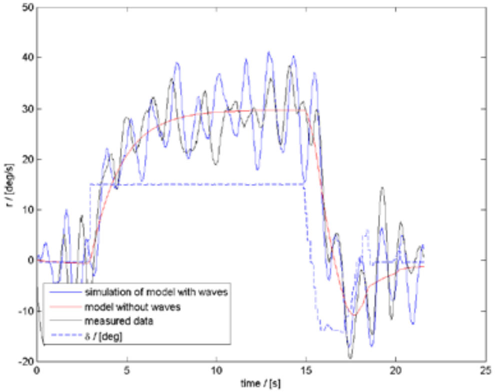
Experiments

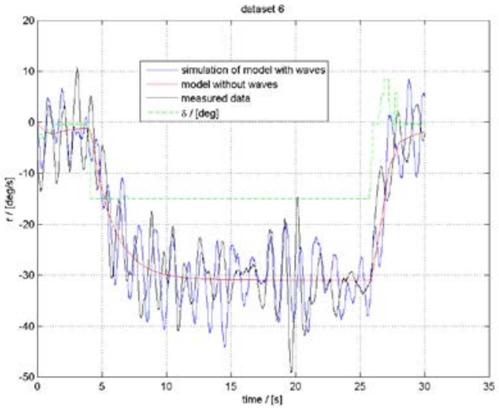
- Yaw from azimuth steps at different elevator deflections

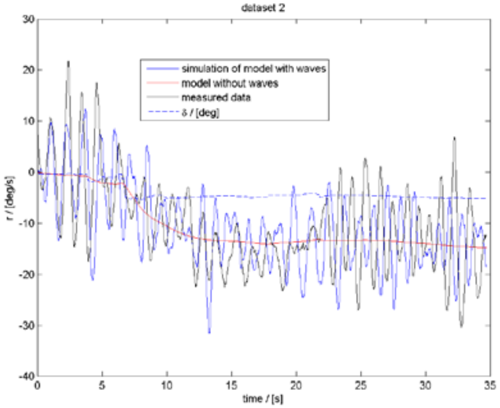










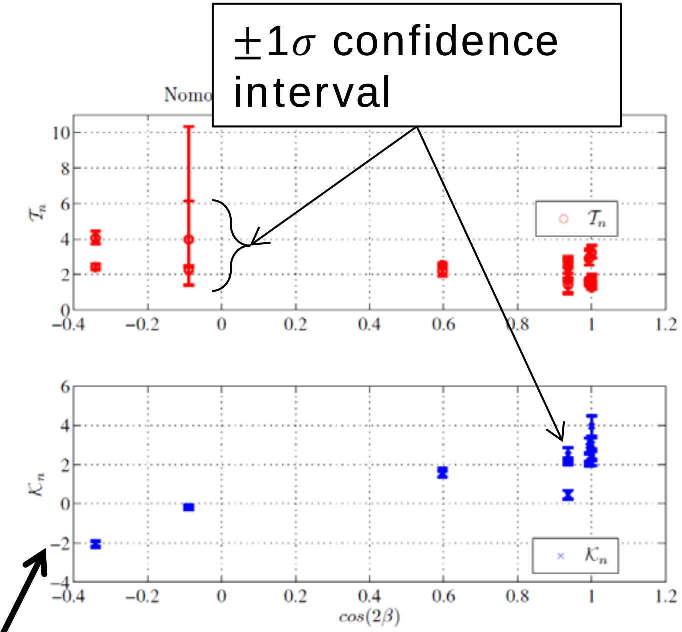


Yaw Dynamics

- Modelled by 1st order Nomoto model with waves

$$r(s) = H_{nom}(s)\delta(s) + r_w(s)\ ,\quad H_{nom} = \frac{K_n}{T_n s + 1}$$

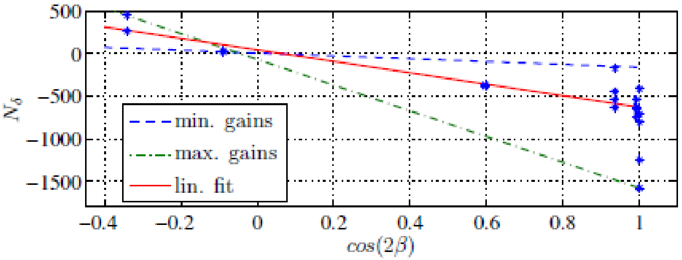
- Circular tests performed at different elevator deflections
- Time constant estimate T_n is uncertain due to disturbances



$\pm 1\sigma$ confidence interval

Estimated parameters of 1st order Nomoto model with 1σ uncertainty.

- Gain K_n is less uncertain
- Gain sign dependends on elevator deflection
  - New input gain: Forced yaw acceleration
  - Uncertain due to parameter variation



Torque gain N as function of elevator angle

Yaw dynamics - discrete time modelling

- Heading error dynamics in discrete time

$$\mathbf{x} \triangleq [\psi_e, r]^{\mathrm{T}} \qquad \psi_e(k) = \psi_{ref}(k) - \psi(k), \ (\psi_e \in] -\pi; \pi])$$

- Discrete time model

$$\begin{aligned} \mathbf{x}(k+1) &= \mathbf{F}\mathbf{x}(k) + \mathbf{g}(\omega u(k) + f(k)) + \mathbf{e} r_w(k) \\ \mathbf{y}(k) &= \mathbf{C}\mathbf{x}(k) + \mathbf{d} r_w(k) \end{aligned}$$

- With system matrices

$$\mathbf{F} = \begin{bmatrix} 1 & \mathcal{T}_n \left(e^{-\frac{T_s}{\mathcal{T}_n}} - 1 \right) \\ 0 & e^{-\frac{T_s}{\mathcal{T}_n}} \end{bmatrix}, \quad \mathbf{g} = \begin{bmatrix} \mathcal{T}_n^2 \left(1 - e^{-\frac{T_s}{\mathcal{T}_n}} - \dfrac{T_s}{\mathcal{T}_n} \right) \\ \mathcal{T}_n \left(1 - e^{-\frac{T_s}{\mathcal{T}_n}} \right) \end{bmatrix}$$

$$\mathbf{e} = \begin{bmatrix} T_s \\ 0 \end{bmatrix}, \quad \mathbf{C} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad \mathbf{d} = \begin{bmatrix} 0 \\ 1 \end{bmatrix},$$

Control objectives

- We want to control the heading ψ at low speeds in presence of
    - Wave disturbances
    - Model uncertainties

Proposed controller – in steps

- Baseline PD-controller designed for nominal dynamics
- Wave filter inserted to limit control action vs HF waves
- L1 adaptive PD augmentation using piecewise constant adaptive law

L1 adaptive control – baseline controller

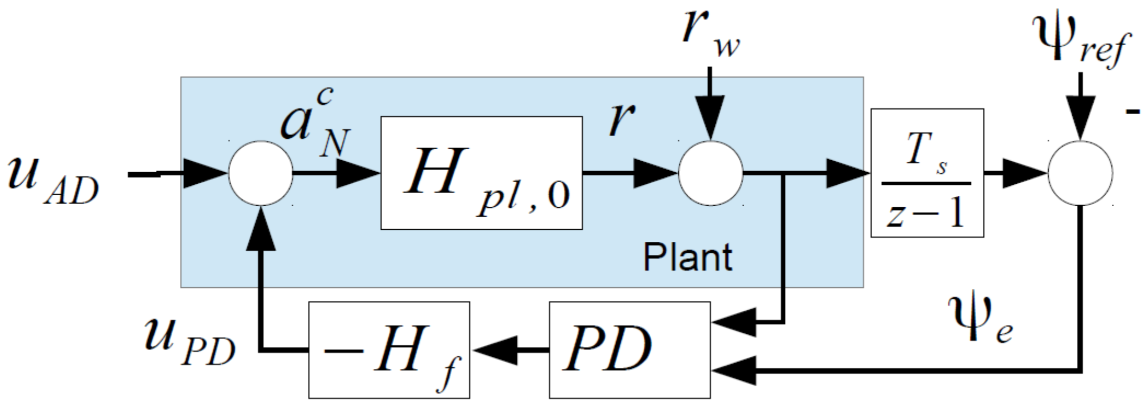
- Nominal dynamics $H_{pl,0}(K_{n0}, T_{n0})$ are chosen

- Controlling heading error

$$\psi_e(k) = \psi(k) - \psi_{ref}(k)$$

- Baseline PD-controller is designed for nominal dynamics

$$u_{PD}(k) = K_p\,\psi_e(k) + K_D r(k)$$

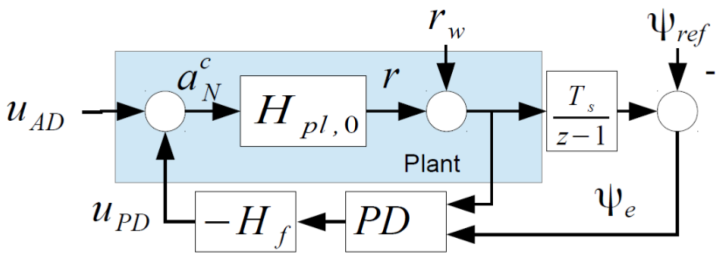


L1 adaptive control – Wave filter

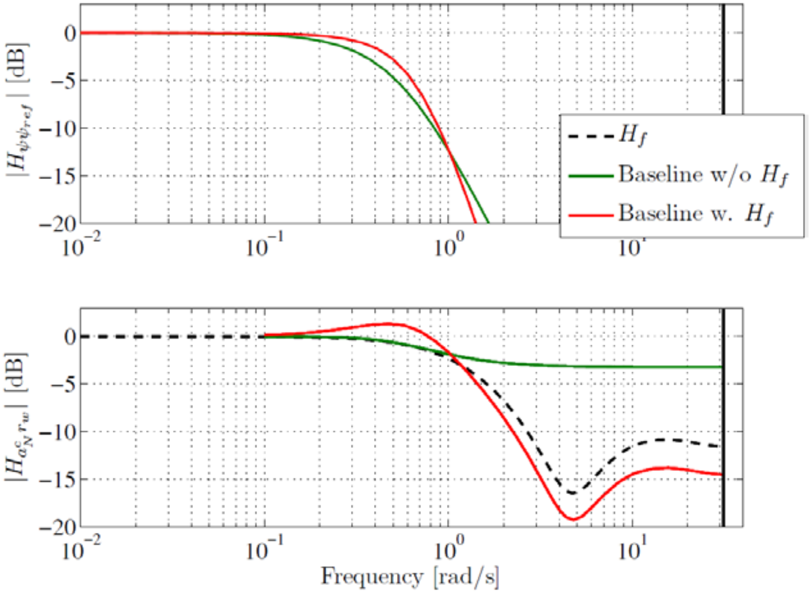
- Augmented with a wave filter

$$H_f(s) = \frac{s^2 + 2\zeta\omega_N s + \omega_N^2}{(s+\omega_N\alpha)(s+\omega_N/\alpha)} \frac{\omega_{lp}}{(s+\omega_{lp})}$$

$$H_f(z) = \frac{k_H(z^2 + 2\zeta_f\omega_{f_1}z + \omega_{f1}^2)}{\left(z - e^{-\alpha_f\omega_{f_1}T_s}\right)\left(z - e^{-\frac{\omega_{f_1}T_s}{\alpha_f}}\right)\left(z - e^{-\omega_{f_2}T_s}\right)}$$



- Limits actuator response towards wave motion
- Baseline controller gives a set of nominal dynamics



- Frequency response
  - Reference model
  - Wave filter

Proposed control strategy

- L1 adaptive PD augmentation using piecewise constant adaptive law
- Physical correlations in yaw dynamics exploited for a simpler controller

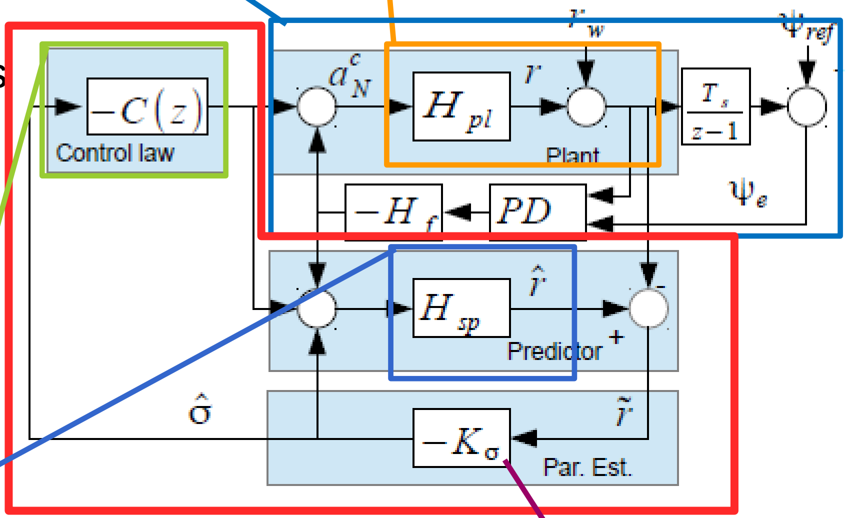
PD baseline controller
With wave filter

Yaw dynamics

L1 adaptive augmentation

- Presented controller allows agile adaptation to unmodelled dynamics
  - Without undesired actuator response to waves

C(z) determines
Adaptation properties



Proposed Contr

State predictor determines the
reference model system adapts to

Estimates disturbance
parameters

Adaptation law and Control law

- The adaptation law $\hat{\sigma}(k) = -g_2^{-1} f_{22} \tilde{r}(k) = -K_\sigma \tilde{r}(k)$
  - Sampling time dependent
  - Small sampling time → large gain

- Control law reduces to $u(z) = -C(z)\hat{\sigma}(z)$
  - Low pass filter C(z), unity DC gain

$$C(s) = \frac{\omega_c^2}{s^2 + 2\zeta_c \omega_c s + \omega_c^2}$$

$$C(z) = \frac{kk_1(z + z_1)}{z^2 + (kk_1 - p_1 - 1)z + p_1 + kk_1 z_1}$$

Robustness analysis

- Relevant transfer-functions in discrete time:
  - Yaw reference to yaw

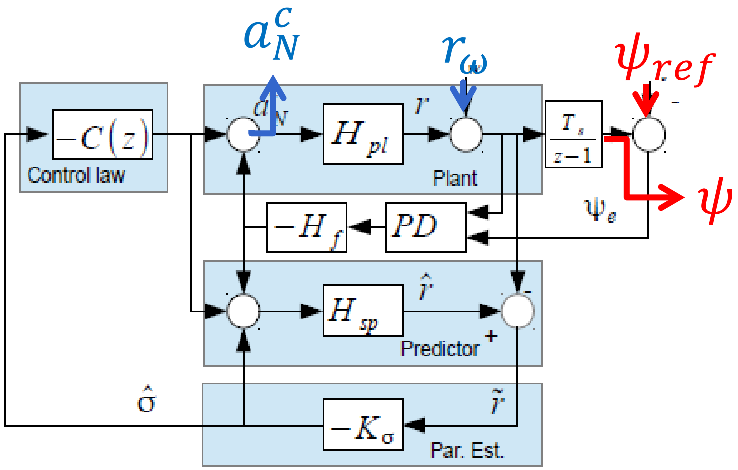
$$H_{\psi\psi_{ref}}(z) = \frac{H_{pl}T_s k_P H_f(1 + H_{sp}K_\sigma)}{d(z)}$$

  - Disturbance to Control signal

$$\begin{aligned} H_{a_N^c r_w}(z) = -(&CK_\sigma z - CK_\sigma + H_f k_D z - H_f k_D \\ &+ H_f k_D H_{sp} K_\sigma z - H_f k_D H_{sp} K_\sigma \\ &+ T_s H_f k_P + T_s H_f k_P H_{sp} K_\sigma)/d(z) \end{aligned}$$

  - With common denominator:

$$\begin{aligned} d(z) = (&z - 1 + H_{sp}K_\sigma z - CH_{sp}K_\sigma z + CH_{sp}K_\sigma \\ &- H_{sp}K_\sigma + H_{pl}T_s k_P H_f + H_{pl}k_D H_f z - H_{pl}k_D H_f \\ &+ H_{pl}K_\sigma C z - H_{pl}K_\sigma C + H_{sp}K_\sigma H_{pl}T_s k_P H_f \\ &+ H_{sp}K_\sigma H_{pl}k_D H_f z - H_{sp}K_\sigma H_{pl}k_D H_f) \end{aligned}$$



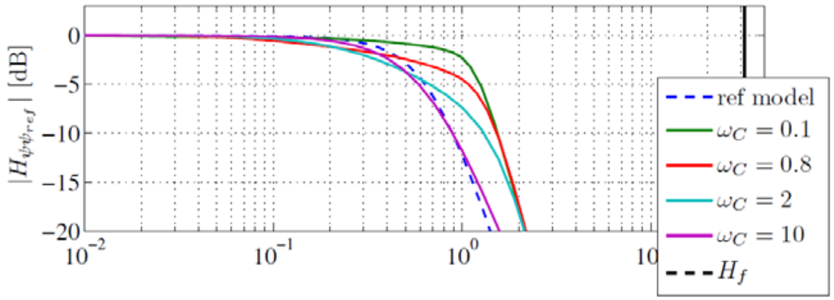
Relevant transfer functions

Robustness analysis

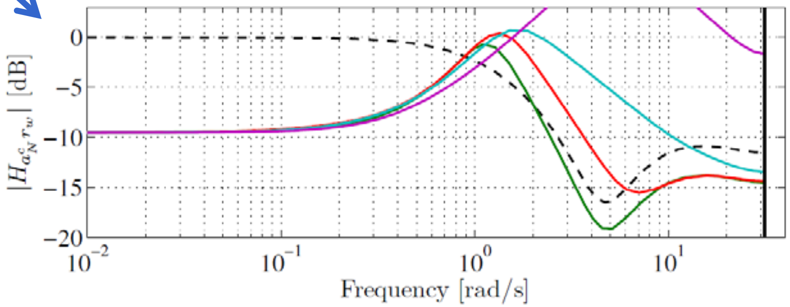
- Relevant transfer-functions
  - Yaw reference to yaw
  - Disturbance to Control signal

- Robustness to parameter uncertainty determined by LP-filter C(z)

- Bandwidth of C(z)
  - High $\omega_c \rightarrow$ Agile adaptation
  - Low $\omega_c \rightarrow$ Less undesired disturbance actuator reponse



Transfer function from heading reference to heading for pertubed gain

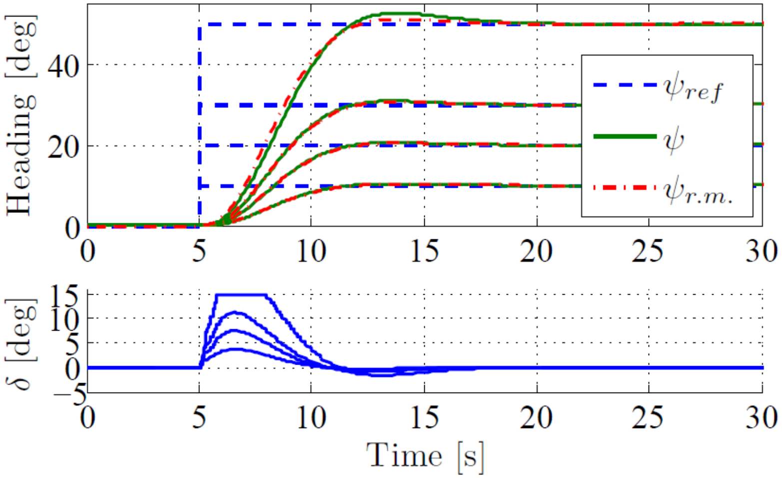


Transfer function from disturbance to control signal

Robustness analysis: C(z) gives a trade-off between adaptation to system's changes and undesired actuation in response to wave motion.

Simulation results

- Scalable uniform transient response to heading reference change
- Allows heading control forwards and aft speed
- Maintains heading in spite of waves (0.5 m)
  without overloading actuator



Scalable uniform transient response

Simulation results

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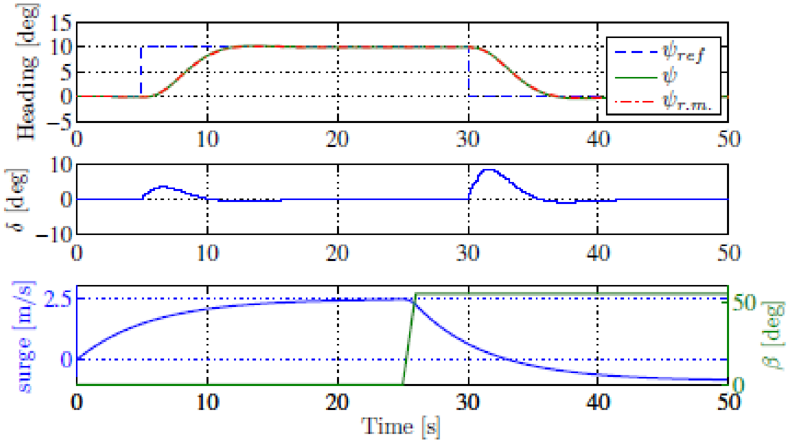

Allows heading control forwards and aft speeds

Simulation results

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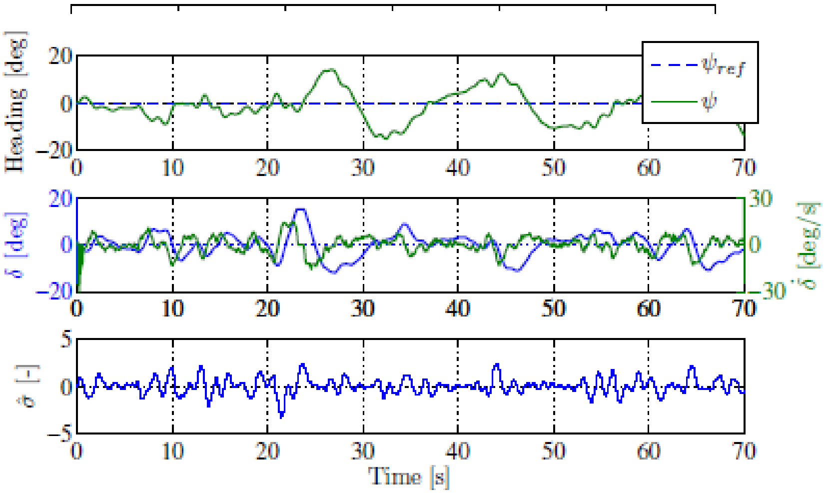

Maintains heading in spite of waves without overloading actuator

Conclusion

- Identified a steering model of the PWC in low-speed and reversing regions based on full scale motion data
  - Large parameter variations in response to similar operational conditions
- A robust adaptive heading controller was designed
  - Designed completely in discrete time
  - combines a baseline PD regulator
  - and a discrete time L1 adaptive controller
- Exploits physical correlations to reduce complexity of the state predictor and the adaptation law
- Robustness analysis included
  - Trade-off between adaptation and actuator response to disturbances
- The proposed heading controller for station keeping purposes was validated by simulations

The presented results are published in proceedings of 9th IFAC conference on Control Applications in Marine Systems, 2013 Osaka, Japan

Related Research

- Cao, C. and Hovakimyan, N. (2009). L1 adaptive outputfeedback controller for non-strictly positive real reference systems: Missile longitudinal autopilot design. AIAA Journal of Guidance, Control, and Dynamics,
- Xargay, E., Hovakimyan, N., and Cao, C. (2010). L1 adaptive controller for multi-input multi-output ssystem in the presence of nonlinear unmatched uncertainties. In Proceedings of the 2010 American Control Conference.
- Svendsen, C.H., Holck, N.O., Galeazzi, R., and Blanke, M. (2012). L1 adaptive manoeuvring control of unmanned high-speed water craft. In Proc. 9th IFAC Conf. on Manoevring and Control of Marine Craft (MCMC'2012).