Seminar on L1 Adaptive Control: Theory & Applications
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L1 Adaptive Manoeuvring Control of Unmanned High-speed Water Craft

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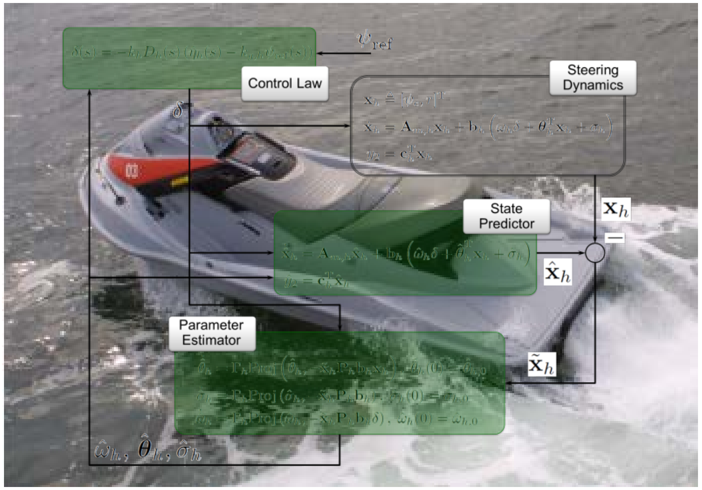

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L1 Adaptive Manoeuvring Control of Unmanned High-speed Water Craft

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Presentation outline

Problem statement	*Motivation & challenges*
Personal watercraft	*The toy & its specs*
Modeling	*Model complexity & identification*
L1 adaptive control	*Maneuvering*
Performance assessment	*Simulations & full scale validation*
Conclusions	*Remarks & research outlook*

Problem statement

Motivation

- What about using high-speed personal watercrafts (PWCs) for coast patrolling, surveillance of installation areas, search & rescue missions?
- Operating the vehicle unmanned represents an opportunity in order to perform tasks safely and reliably however seaworthiness must be guaranteed across a large range of operational conditions

Challenges

- Well known DYNAMIC STABILITY issues (e.g. porpoising, bow diving, difficulty of course keeping, etc.)

Safety of the PWC and of its mission

PWC manoeuvring capabilities

Challenges for maneuvering control

Maneuvering

- Manoeuvring characteristics influenced by the vehicle’s vertical dynamics
- Towing tank tests have shown that hydrodynamic forces/moments acting on a planing craft strongly depend on the running attitude (Ikeda, 2000)

which
nonlinear models?

Low speed

Medium to high speed

High speed + waves

Proposed solution

Control Objective: operate the high-speed PWC with equal performance across the craft's full envelope of operations

Modeling

- Model the manoeuvring characteristics through **REDUCED COMPLEXITY MODELS** (4DOF surge-sway-yaw-roll model / 1DOF yaw model)
- Identify the models through mixed black-box/grey-box identification exploiting **FULL SCALE MOTION DATA**

Control

- Design a **ROBUST ADAPTIVE MANOEUVRING CONTROLLER** capable of dealing with rapid and large changes of the PWC dynamics

System setup

- Vehicle
  - modified Sea-Doo GTX 215 PWC
- Extra Actuation
  - 1 servo for throttle control
  - 1 servo for controlling the azimuth angle of the propulsion system
  - 1 servo for controlling the elevator angle of a blade
- Communication
  - radio receiver for remote control
- Measurement System
  - GPS
  - 9DOF IMU

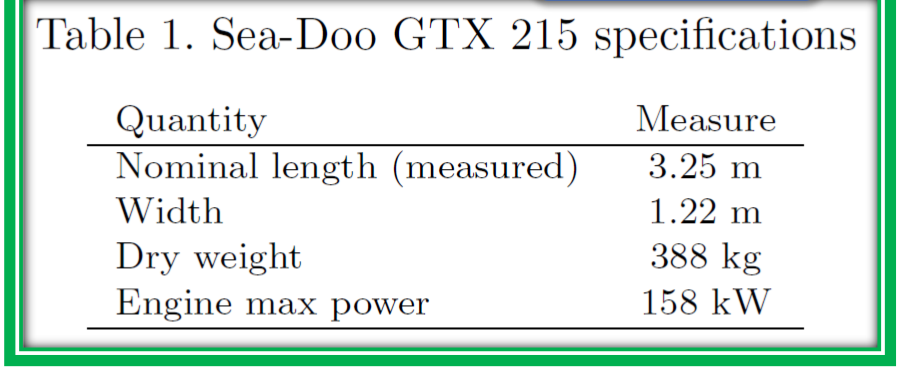


Table 1. Sea-Doo GTX 215 specifications

Quantity	Measure
Nominal length (measured)	3.25 m
Width	1.22 m
Dry weight	388 kg
Engine max power	158 kW

PWC maneuvering dynamics

- Maneuvering dynamics described by 4DOF surge-sway-yaw-roll model (according to Blanke & Christensen, 1993)

$$\begin{aligned}\boldsymbol{\eta} &= [x, y, \phi, \psi]^{\mathrm{T}} \in \mathbb{R}^2 \times \mathcal{S}^2 \\ \boldsymbol{\nu} &= [u, v, p, r]^{\mathrm{T}} \in \mathbb{R}^4 \\ \mathbf{r}_g &= [0, 0, z_g]^{\mathrm{T}} \in \mathbb{R}^3\end{aligned}$$

Generalized coordinates

Generalized velocities

Position of CG

$$\boxed{\mathbf{M}\dot{\boldsymbol{\nu}} + (\mathbf{C}(\boldsymbol{\nu}) + \mathbf{D}(\boldsymbol{\nu}))\boldsymbol{\nu} + \mathbf{g}(\boldsymbol{\eta}) = \boldsymbol{\tau}_c + \tau_e}$$

- Identification performed using **FULL SCALE MOTION DATA**

$$\boldsymbol{\tau}_e = \mathbf{0}$$

$$\boxed{\dot{\boldsymbol{\nu}} = -\mathbf{M}^{-1}\left[(\mathbf{C}(\boldsymbol{\nu}) + \mathbf{D}(\boldsymbol{\nu}))\boldsymbol{\nu} + \mathbf{g}(\boldsymbol{\eta})\right] + \mathbf{M}^{-1}\boldsymbol{\tau}_c}$$

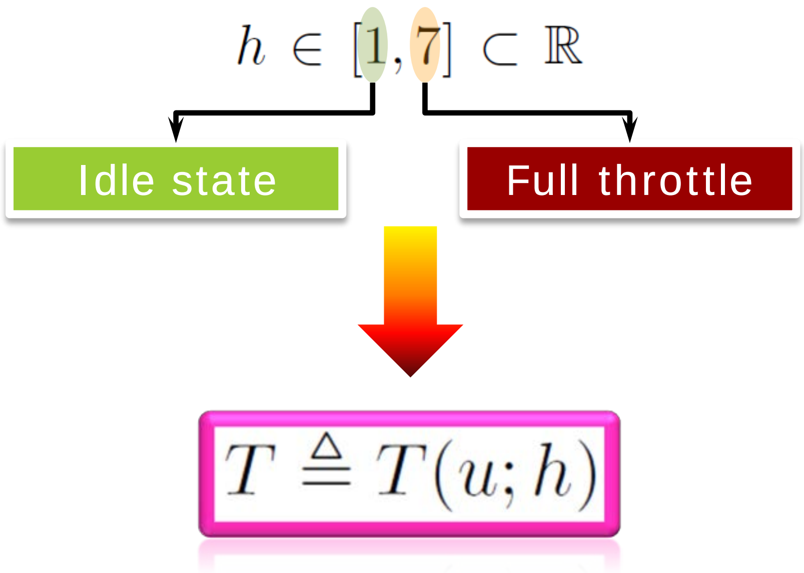
Surge dynamics identification (1/2)

Surge Dynamics

$$\left(m - X_{\dot u}\right)\dot u - \left(X_u + X_{u|u|}\left|u\right|\right)u + \left(m z_g + Y_{\dot p}\right)pr - \left(m - Y_{\dot v}\right)vr + Y_{\dot r}r^2 = \tau_u$$

$$\tau_u = (1 - t)T(n, u_p)$$

- $T(n,u_p)$ is not measured and there is no direct control of the shaft speed n
- Only the handle command h is available



$$h \in [1, 7] \subset \mathbb{R}$$

Idle state

Full throttle

$$\boxed{T \triangleq T(u; h)}$$

Surge dynamics identification (2/2)

Identification

- Estimate advance resistance coefficients from surge data in response to steps in the handle command
- Determine steady state relations between T and u

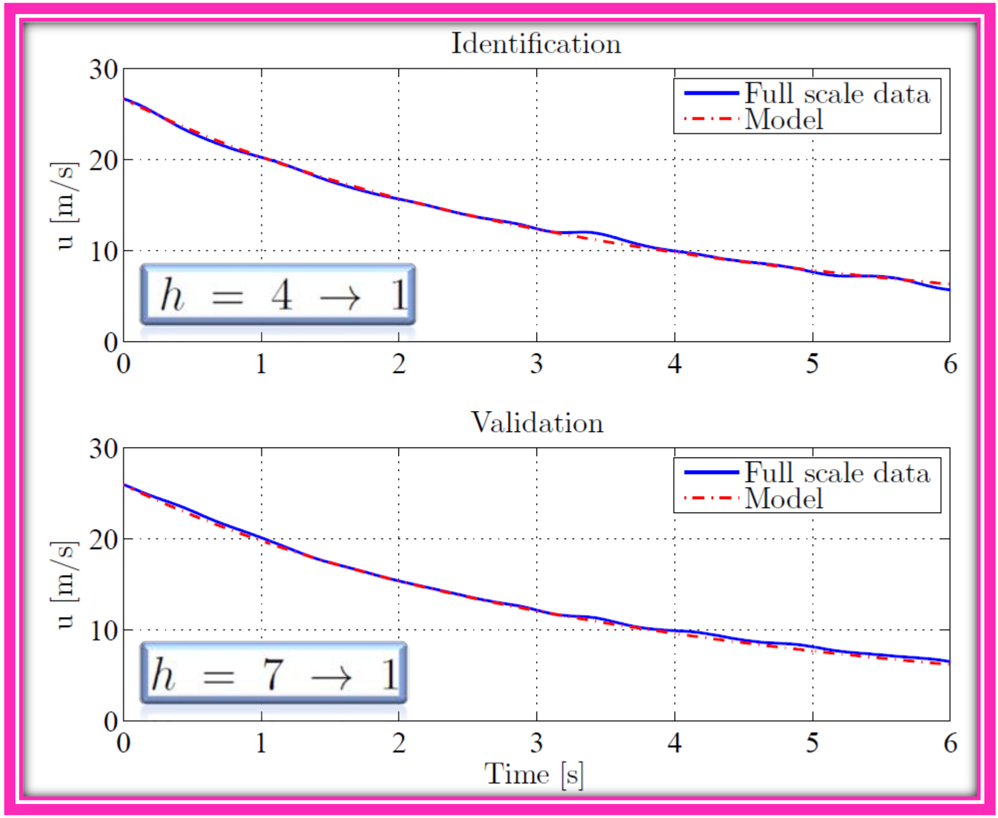
Straight course in calm water

$$\dot{u} = \alpha_1 u + \alpha_2 u|u| + \tilde{\tau}_u$$

$$t = t_0 \rightarrow u\left(t_0\right) = \bar{u} = \text{const}$$

$$\tilde{\tau}_u = \begin{cases} \bar{\tau}_u > 0, & t < t_0 \\ 0, & t \geq t_0 \end{cases}$$

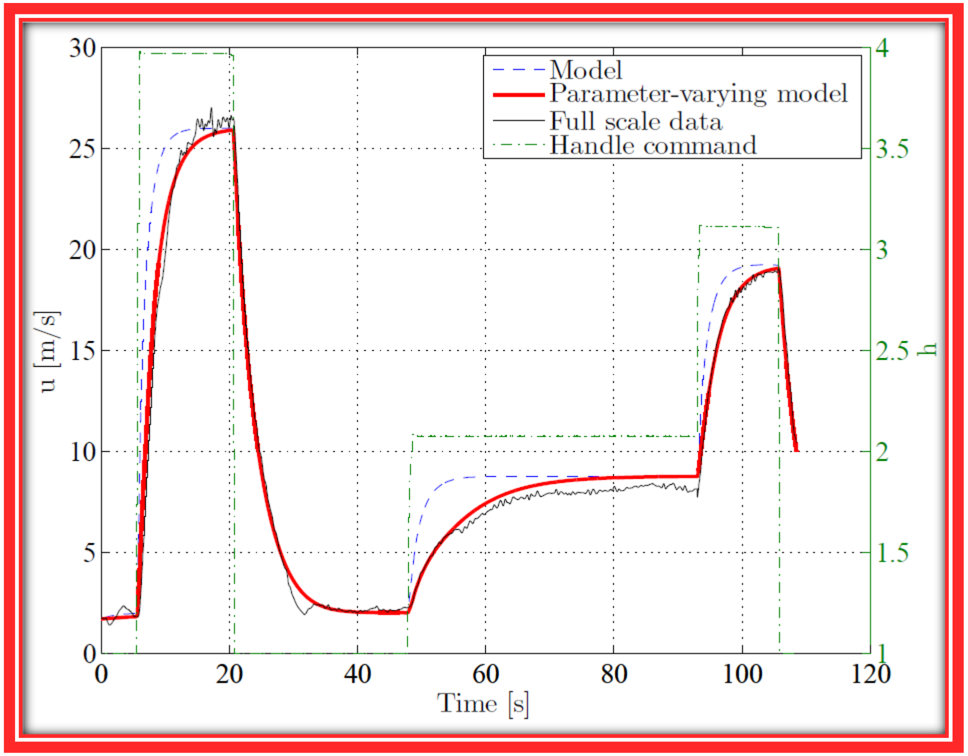
$$u(t) \leq \bar{u} e^{-\alpha_1 t}, \quad \forall\, t > t_0$$



Surge dynamics validation

Validation

- Against **FULL SCALE MOTION DATA**
- Four consecutive step changes in the handle command

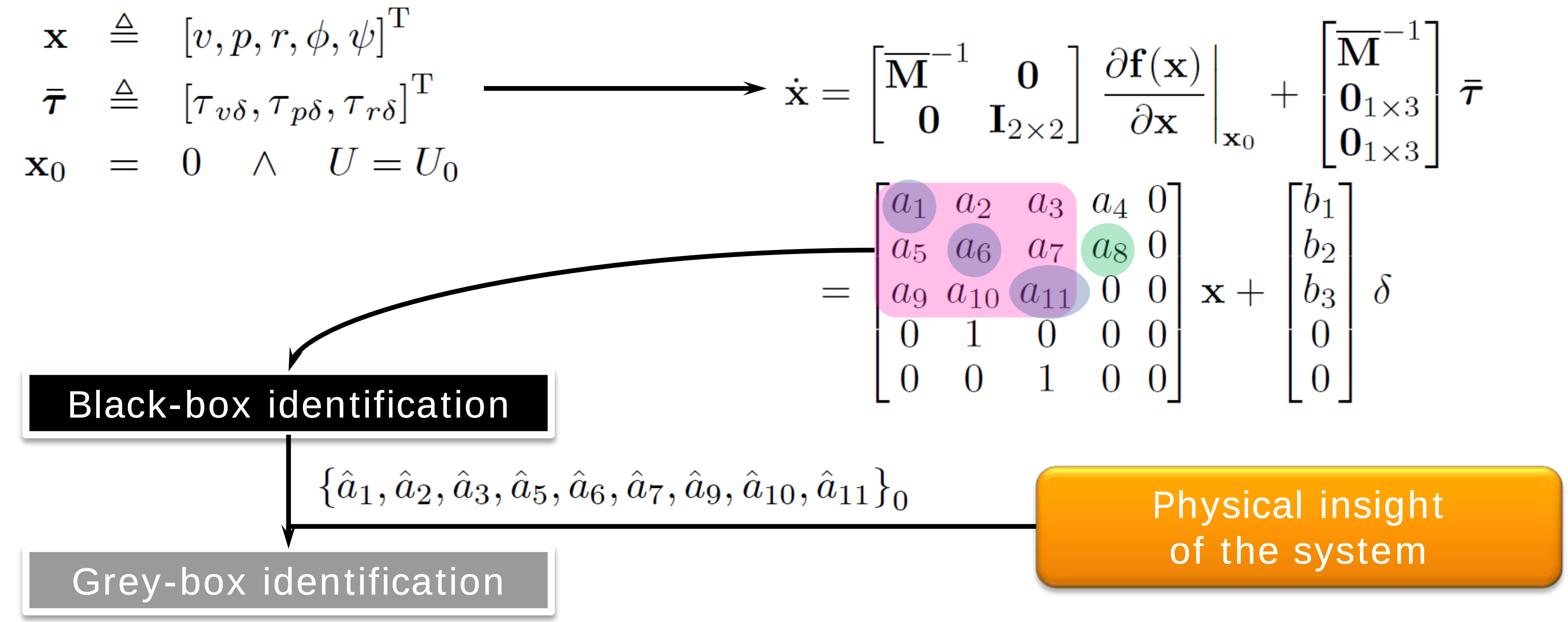


$$\dot{u} = \kappa(\alpha_1 u + \alpha_2 u|u| + \tilde{\tau}_u), \quad \kappa \in [0.2, 1]$$

Steering + roll dynamics identification

Identification

- Fitting a linearized 3DOF sway-roll-yaw model
- **FULL SCALE DATA** from circular tests and zig-zag tests



$$\mathbf{x} \triangleq [v,p,r,\phi,\psi]^{\mathrm{T}}$$

$$\bar{\boldsymbol{\tau}} \triangleq [\tau_{v\delta},\tau_{p\delta},\tau_{r\delta}]^{\mathrm{T}}$$

$$\mathbf{x}_0 = 0 \quad \wedge \quad U = U_0$$

$$\dot{\mathbf{x}} = \begin{bmatrix}\overline{\mathbf{M}}^{-1} & \mathbf{0}\\ \mathbf{0} & \mathbf{I}_{2\times2}\end{bmatrix} \left.\frac{\partial \mathbf{f}(\mathbf{x})}{\partial \mathbf{x}}\right|_{\mathbf{x}_0} + \begin{bmatrix}\overline{\mathbf{M}}^{-1}\\ \mathbf{0}_{1\times3}\\ \mathbf{0}_{1\times3}\end{bmatrix}\bar{\boldsymbol{\tau}}$$

$$= \begin{bmatrix} a_1 & a_2 & a_3 & a_4 & 0\\ a_5 & a_6 & a_7 & a_8 & 0\\ a_9 & a_{10} & a_{11} & 0 & 0\\ 0 & 1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0 & 0\end{bmatrix}\mathbf{x} + \begin{bmatrix}b_1\\ b_2\\ b_3\\ 0\\ 0\end{bmatrix}\delta$$

Black-box identification

$$\{\hat{a}_1,\hat{a}_2,\hat{a}_3,\hat{a}_5,\hat{a}_6,\hat{a}_7,\hat{a}_9,\hat{a}_{10},\hat{a}_{11}\}_0$$

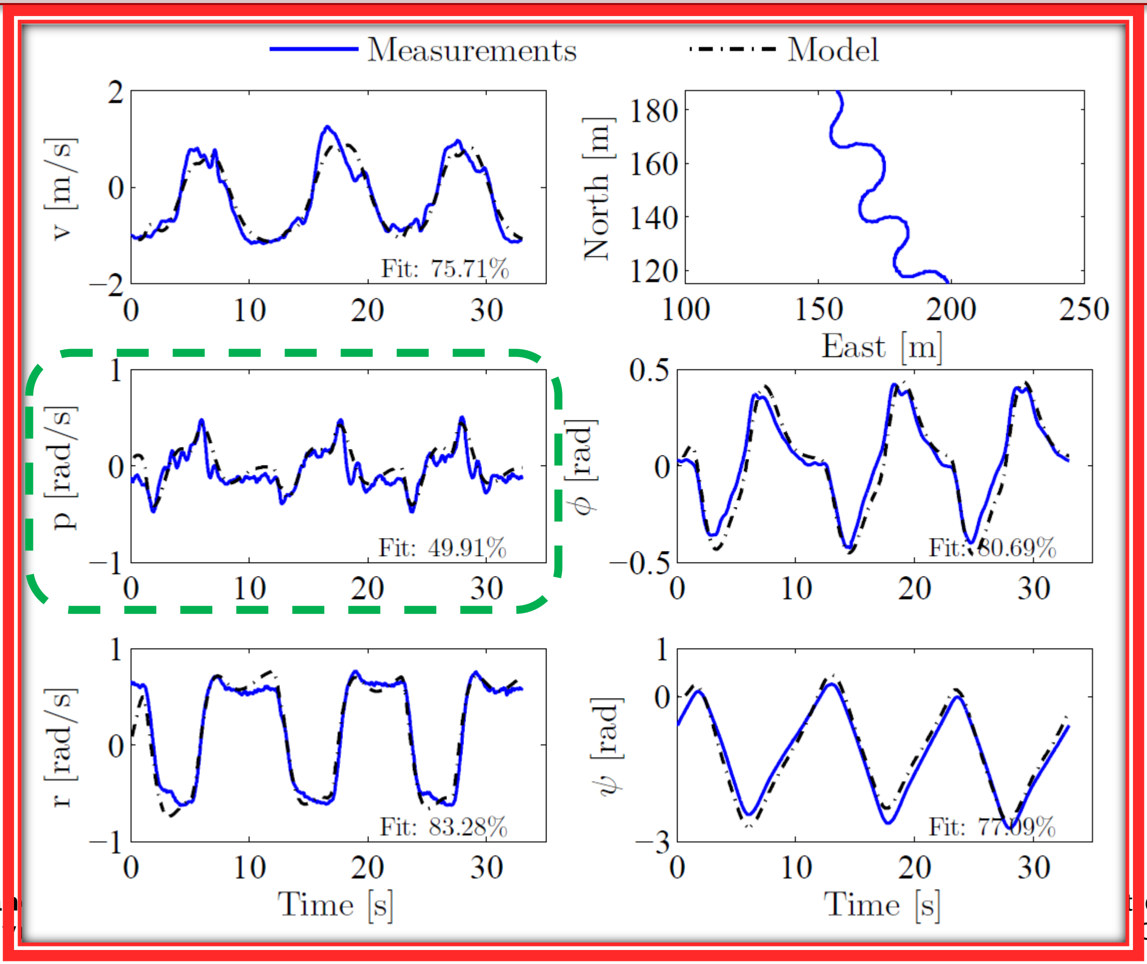
Physical insight of the system

Grey-box identification

Steering + roll dynamics validation

Validation

- Against **FULL SCALE DATA** of a 15-90 zig-zag test

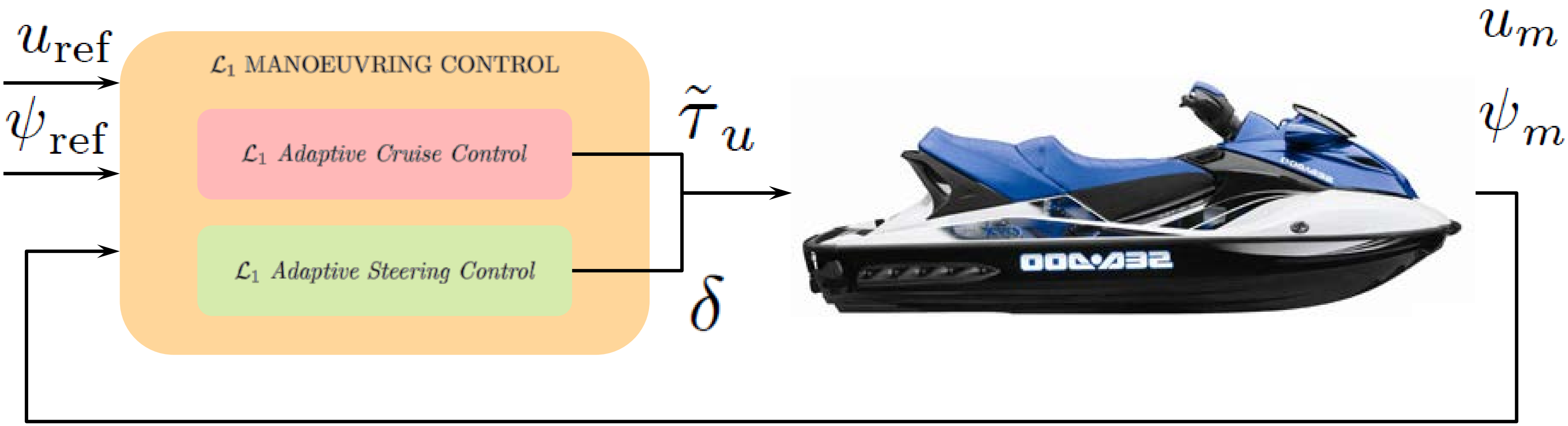


Adaptive manoeuvring control

Why an adaptive controller?

- Both surge and steering appear to be dependent on the running attitude
- Forward speed has a substantial influence on the steering characteristics
- Surge dynamics shows different behaviors during positive and negative accelerations
- Constraining the modeling of the steering dynamics on the horizontal plane naturally exclude the effect of the vertical motions which are known to be relevant for planing crafts (Ikeda, 2000)

L1 adaptive manoeuvring control



u_{ref}

ψ_{ref}

$\mathcal{L}_1$ MANOEUVRING CONTROL

$\mathcal{L}_1$ Adaptive Cruise Control

$\mathcal{L}_1$ Adaptive Steering Control

$\tilde{\tau}_u$

δ

u_m

ψ_m

$\mathcal{L}_1$ Adaptive Cruise Control

Surge Dynamics

$$\dot{u} = A_{m,u}u + (\omega_u \tilde{\tau}_u + g(t,u) + \sigma_u)$$

$$y_1 = u$$

$$A_{m,u} = \alpha_{\text{des}} \in \mathbb{R}^-$$

$$\omega_u = \kappa(t) \in R^+$$

$$\sigma_u = \alpha_3(t)vr$$

State Predictor

$$\dot{\hat{u}} = A_{m,u}\hat{u} + \left(\hat{\omega}_u \tilde{\tau}_u + \hat{\theta}_u \|u\|_\infty + \hat{\sigma}_u\right),\ \hat{u} = u_0$$

$$\hat{y}_1 = \hat{u}$$

Parameter Estimator

$$\dot{\hat{\theta}}_u = \Gamma_u \text{Proj}\left(\hat{\theta}_u, -\tilde{u}P_u \|u\|_\infty\right),\ \hat{\theta}_u(0) = \hat{\theta}_{u,0}$$

$$\dot{\hat{\sigma}}_u = \Gamma_u \text{Proj}\left(\hat{\sigma}_u, -\tilde{u}P_u\right),\ \hat{\sigma}_u(0) = \hat{\sigma}_{u,0}$$

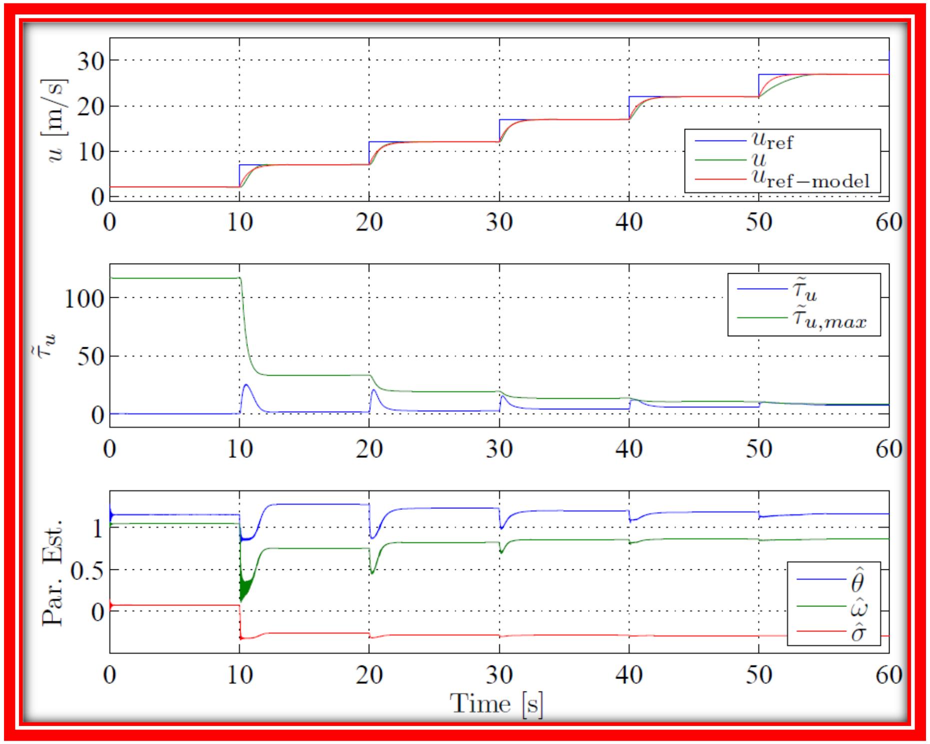
$$\dot{\hat{\omega}}_u = \Gamma_u \text{Proj}\left(\hat{\omega}_u, -\tilde{u}P_u\tilde{\tau}_u\right),\ \hat{\omega}_u(0) = \hat{\omega}_{u,0}$$

Control Law

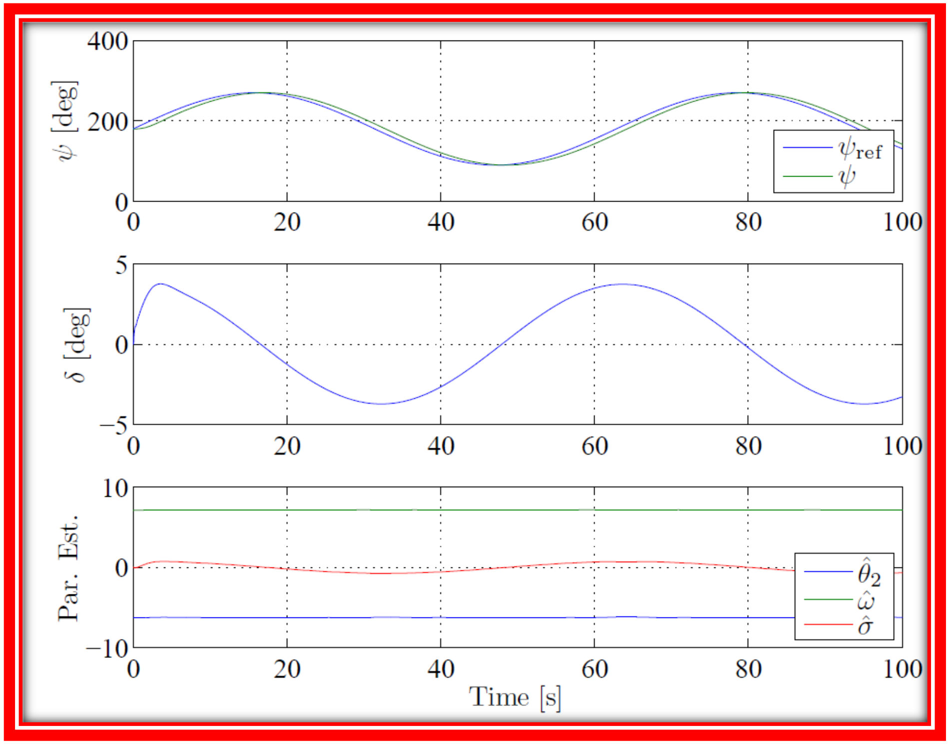
$$\tilde{\tau}_u(s) = -k_u D_u(s)\left(\hat{\eta}_u(s) - k_{g,u}u_{\text{ref}}(s)\right)$$

Testing of L1 adaptive manoeuvring control

Cruise controller



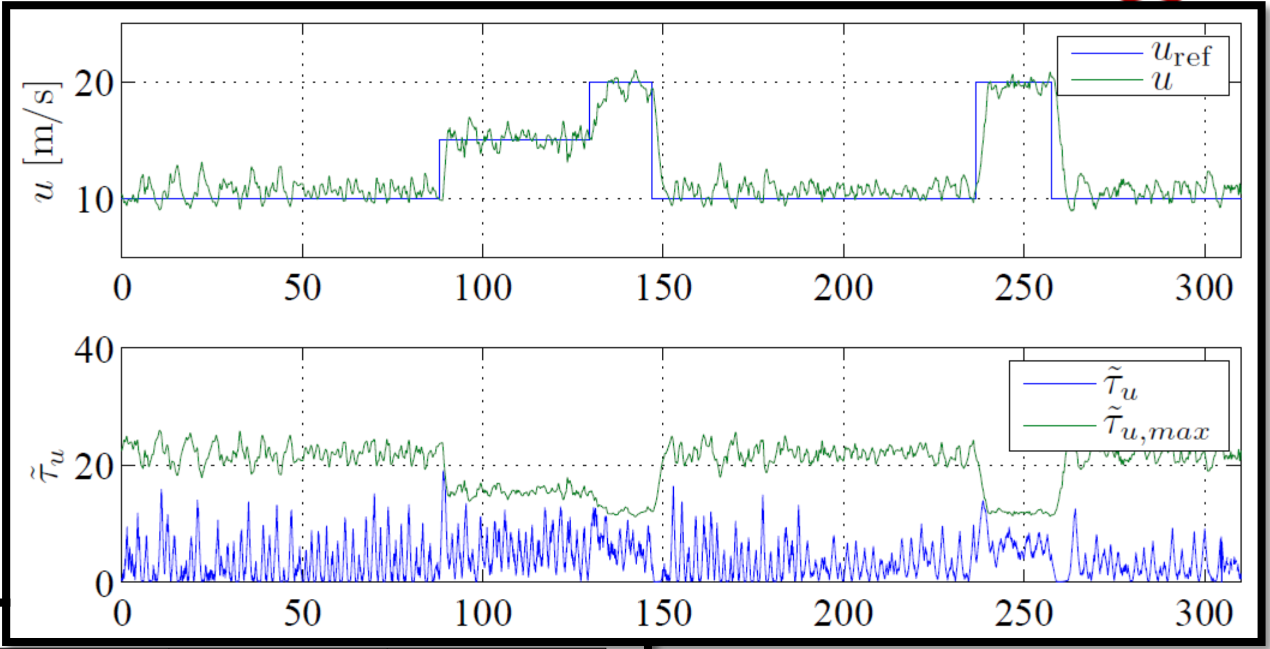
Steering controller

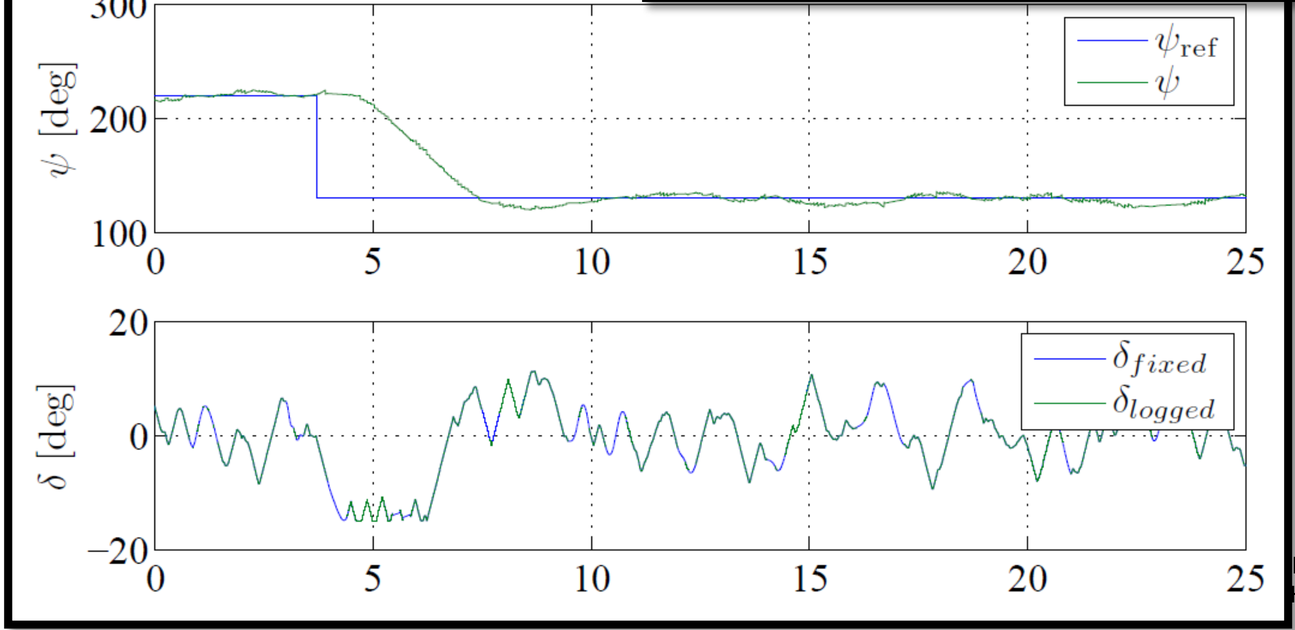


Full scale validation of L1 adaptive manoeuvring control

Full scale validation of L1 adaptive manoeuvring control

Cruise controller





Steering controller

Conclusions

Identification

- 4DOF surge-sway-yaw-roll model has been identified for the high-speed PWC based on FULL SCALE MOTION DATA
- Clear dependence of the maneuvering characteristics on the running attitude

Control Design

- L1 adaptive maneuvering autopilot has been designed in order to have uniform performances across the entire operational range of the vehicle
- Design split into an adaptive cruise controller and an adaptive steering controller

Validation

- Simulations and full scale closed loop tests shows convincing performance of the L1 adaptive maneuvering controller and of the L1 augmented station keeping (heading) controller

Conclusions

Detailed results can/will be found in the following publications:

- Svendsen, C. H., Holck, N. O., Galeazzi, R., Blanke, M. "**L1 Adaptive Manoeuvring Control of Unmanned High-speed Water Craft**" in *Proceedings of the 9th IFAC Conference on Manoeuvring and Control of Marine Crafts*, 2012 (**Best Paper Award**)
- Galeazzi, R. Holck, N. O., Svendsen, C. H., Blanke, M. "**Full Scale Validation of L1 Adaptive Autopilot of Unmanned High-speed Water Craft**", to be submitted (as soon as possible)
- Svendsen, C. H., Holck, N. O. "**L1 Adaptive Control of Waterjet Vehicle**", MSc Thesis, Technical University of Denmark, 2012

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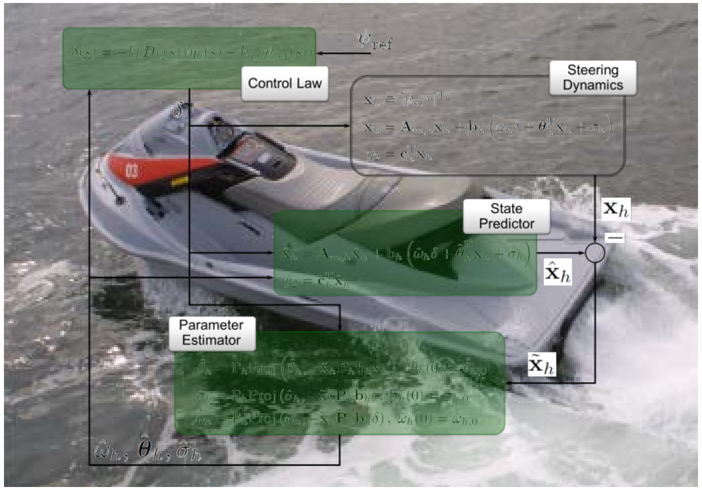

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