A Novel Application of Multivariable $\mathcal{L}_1$ Adaptive Control: from Design to Real-Time Implementation on an Underwater Vehicle

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Outline

I. Introduction: Problems/Challenges

II. Proposed Control Scheme

III. Dynamic Modeling

IV. Experimental Results

V. Conclusion

AC-ROV (Access Ltd)

Actuation: - 6 thrusters
- 5 actuated DOF

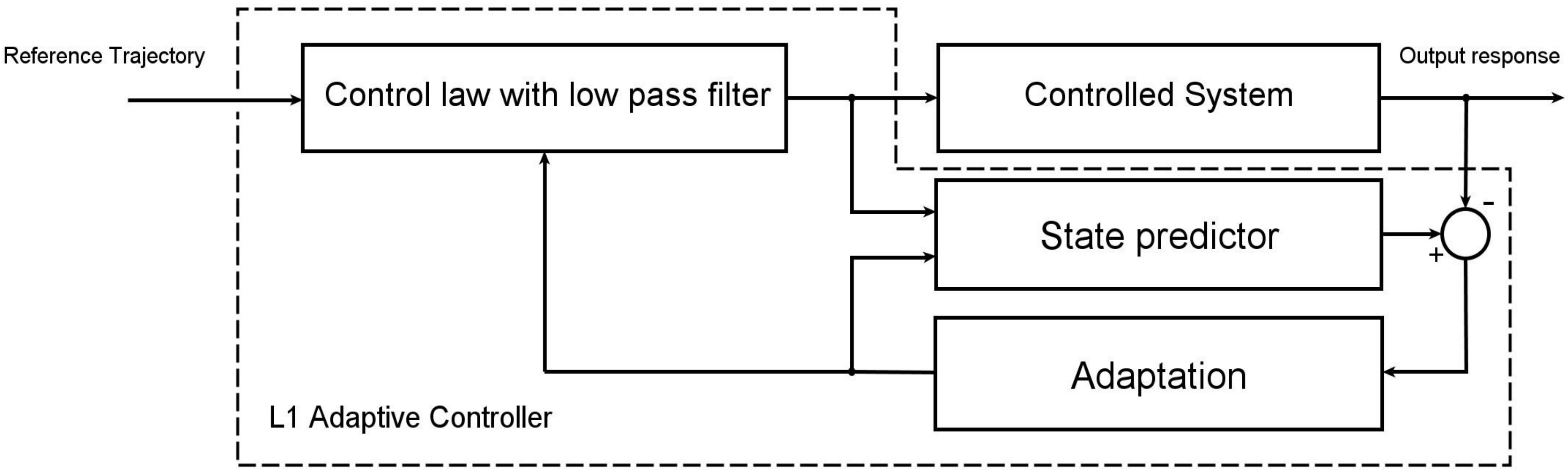
Sensors:
- IMU
- Camera
- Depth Sensor

Objective

Control of a small underwater vehicle in presence of parameter uncertainties and external disturbances.

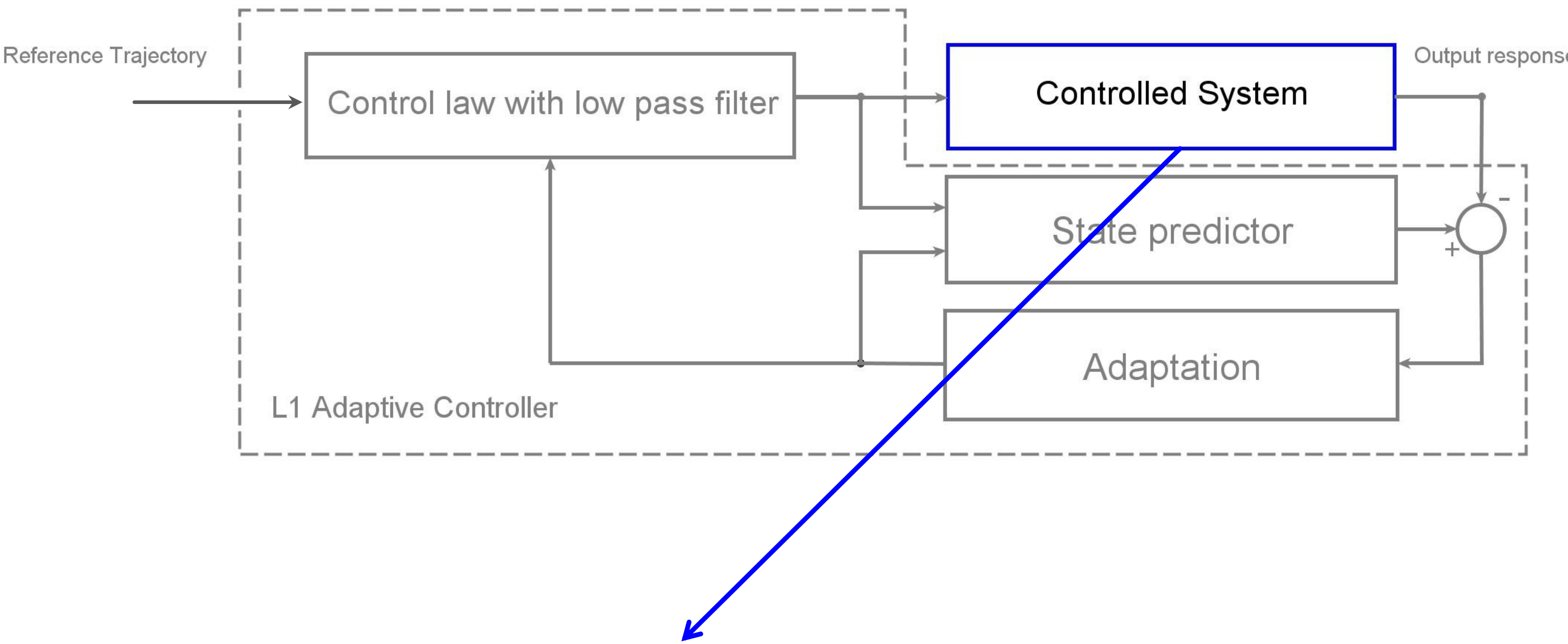
Controller

$\mathcal{L}_1$ Adaptive Controller Architecture



- Recently developed controller decoupling robustness and adaptation [Hovakimyan2010]
- Validated performance through experimental results in flight control
- Implemented in various systems mainly aerial vehicles but never in underwater ones

$\mathcal{L}_1$ Adaptive Controller Architecture

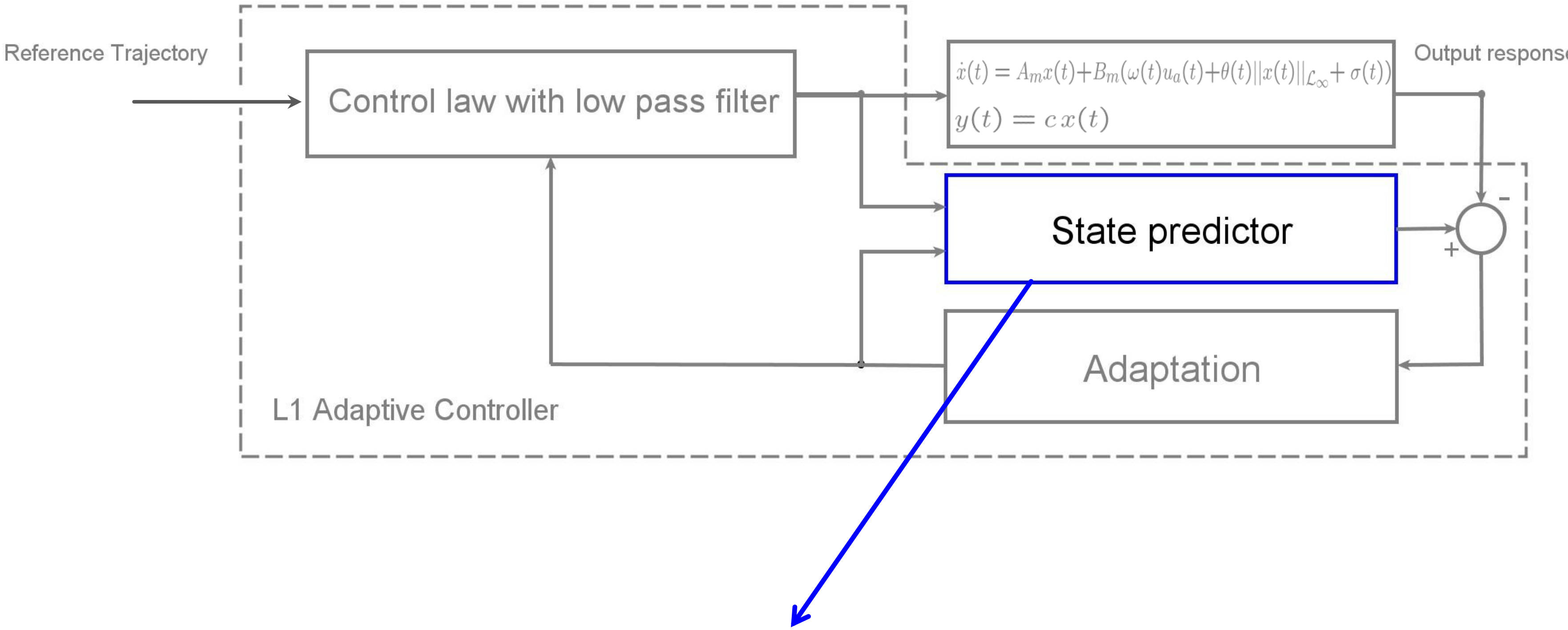


$$\dot{x}(t) = A$$
$$y(t) = C$$

$$\dot{x}_1(t) = x_2(t)$$
$$\dot{x}_2(t) = f_2(t, x(t)) + B_2 \omega u$$
$$y(t) = Cx(t)$$

$$x(t)||_{\mathcal{L}_\infty} + \sigma(t))$$

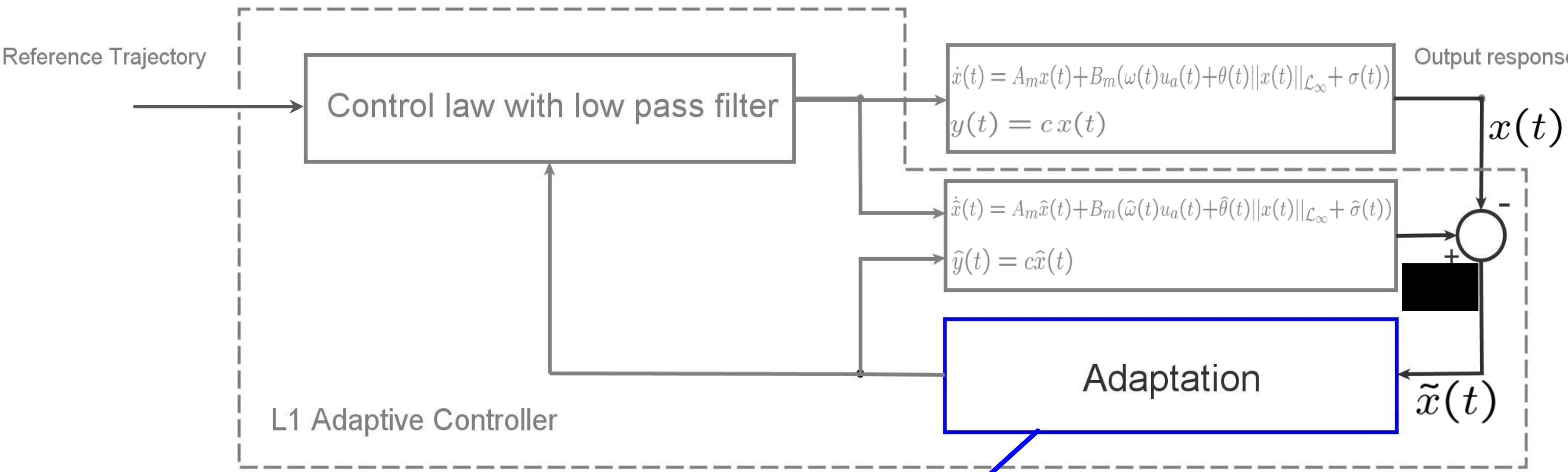
$\mathcal{L}_1$ Adaptive Controller Architecture



$$\dot{\hat{x}}(t) = A_m\hat{x}(t) + B_m(\hat{\omega}(t)u_a(t) + \hat{\theta}(t)||\hat{x}(t)||_{\mathcal{L}\infty} + \hat{\sigma}(t))$$

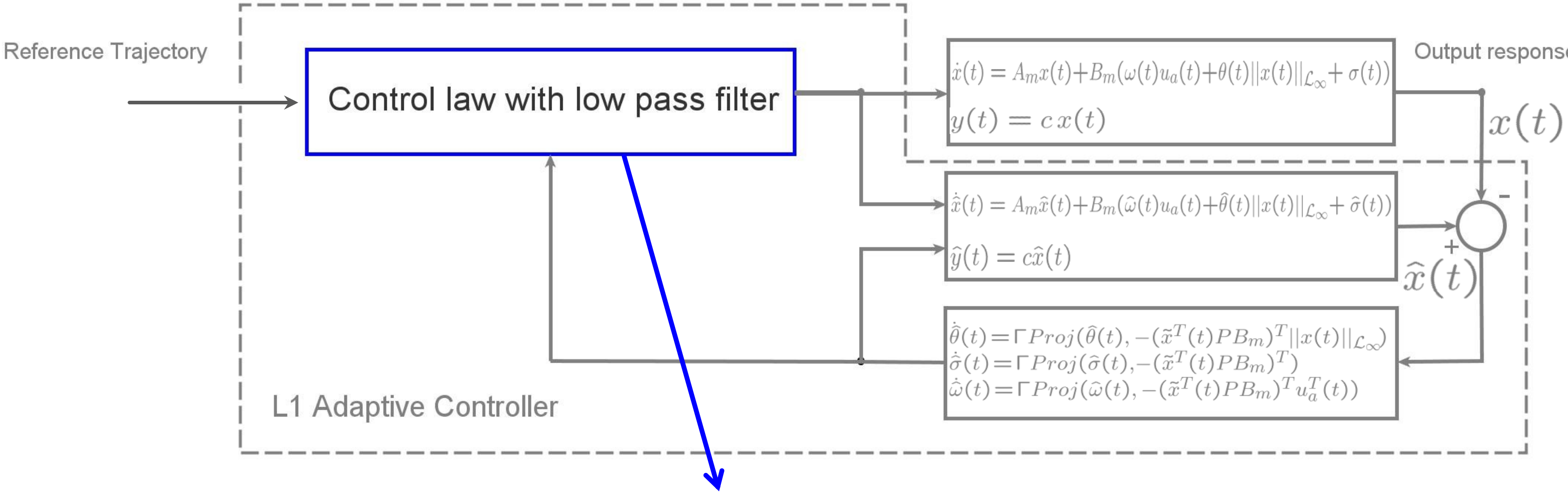
$$\hat{y}(t) = C\hat{x}(t)$$

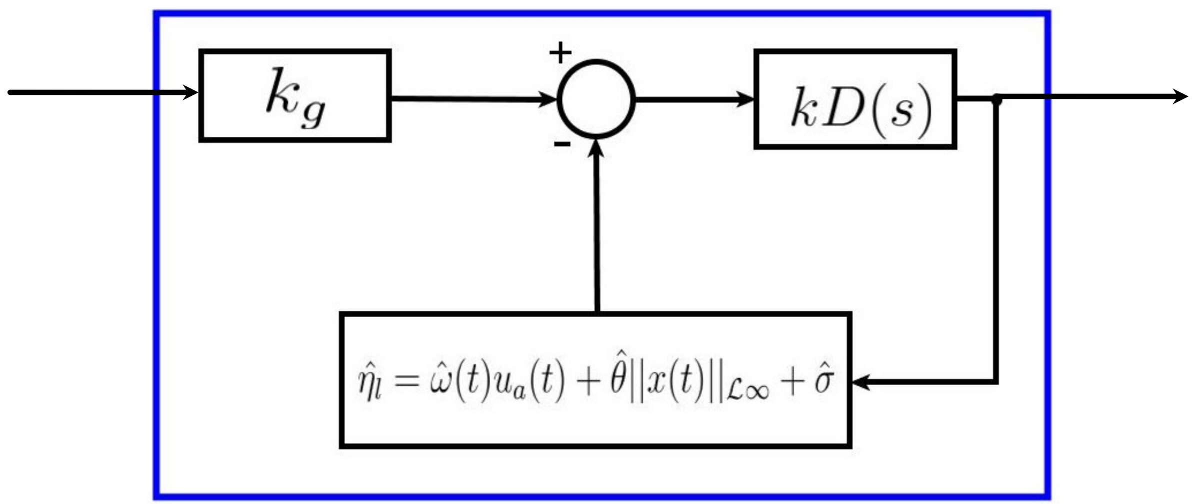
$\mathcal{L}_1$ Adaptive Controller Architecture



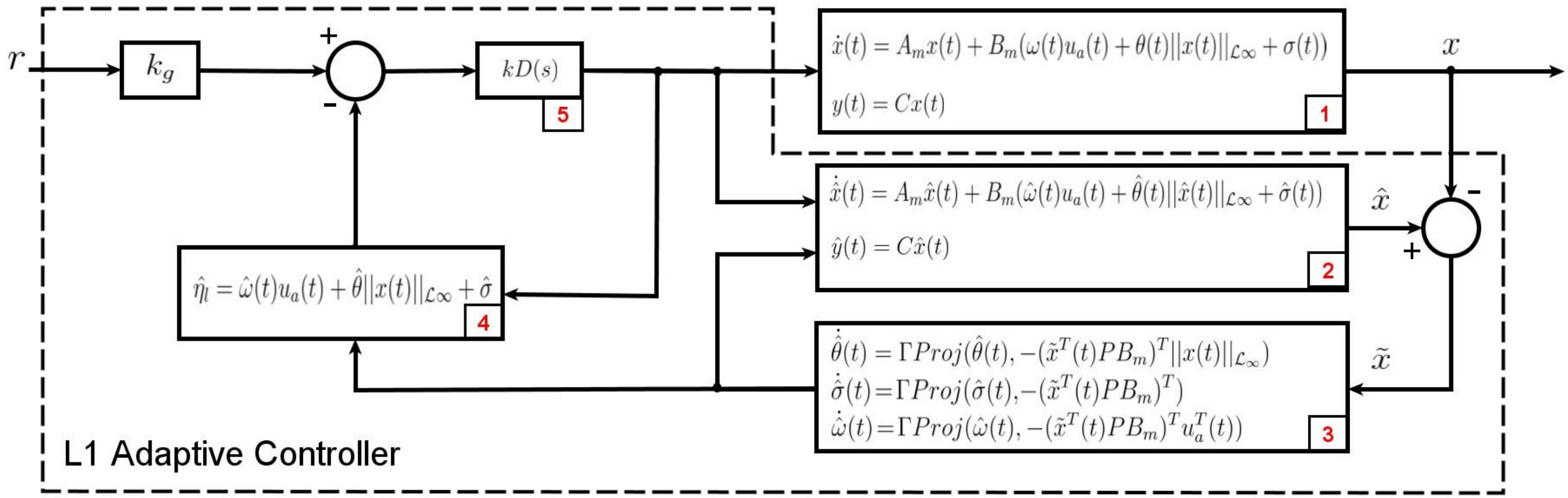
$$\dot{\hat{\theta}}(t) = \Gamma Proj(\hat{\theta}(t), -(\tilde{x}^T(t) P B_m)^T ||x(t)||_{\mathcal{L}_\infty})$$
$$\dot{\hat{\sigma}}(t) = \Gamma Proj(\hat{\sigma}(t), -(\tilde{x}^T(t) P B_m)^T)$$
$$\dot{\hat{\omega}}(t) = \Gamma Proj(\hat{\omega}(t), -(\tilde{x}^T(t) P B_m)^T u_a^T(t))$$

$\mathcal{L}_1$ Adaptive Controller Architecture





$\mathcal{L}_1$ Adaptive Controller Architecture Summary



1	Controlled system
2	Prediction phase
3	Parameter update
4- 5	Control input, with feedback gain k , pre-filter k_g and filter $D(s)$

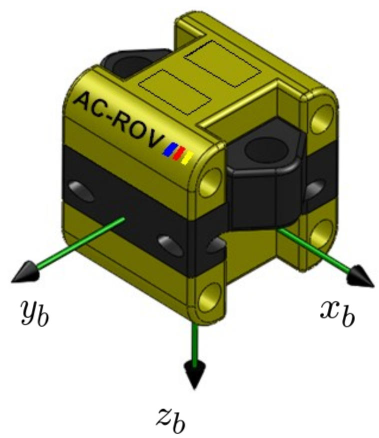
Modeling

Motion Variables for a Marine Vessel

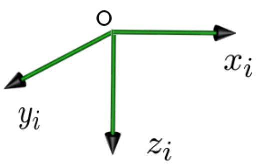
φ: rotation/x_i

ψ: rotation/y_i

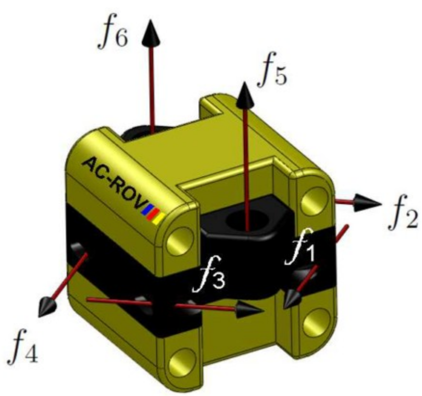
ϑ: Rotation/z_i



Earth frame



Forces produced by the thrusters



Dynamic Modeling [Fossen2002]

$$M\dot{\nu} + C(\nu)\nu + D(\nu)\nu + G(\eta) = \tau + w_d$$

$$\dot{\eta} = J(\eta)\nu$$

$$\nu = [u\ v\ w\ p\ q\ r]^T$$

Vector of velocities in the body fixed frame

$$\eta = [x\ y\ z\ \varphi\ \vartheta\ \psi]^T$$

Vector of positions in the earth fixed frame

$M, C(\nu), D(\nu)$

Model matrices (Mass, Coriolis, Damping)

$G(\eta)$

Vector of gravitational / buoyancy forces

τ *Vector of control inputs*

w_d *Vector of external disturbances*

J *Transformation matrix*

Equation of dynamic model in the body-fixed frame

$$M\dot{v} + \cancel{C(v)}v + D(v)v + G(\eta) = \tau + w_d$$

$\dot{\eta} = J(\eta)v$

Equation of the reduced dynamic model in the earth-fixed frame

$$M_r^*(\eta)\ddot{\eta}_r + D_r^*(\eta)\dot{\eta}_r + g_r^*(\eta) = \tau_r^*(\eta) + w_{d_r}^*(\eta)$$

Studied Dynamics

Position of center of gravity — Weight — Buoyancy

$$\begin{bmatrix} M_z^* & 0 \\ 0 & M_\vartheta^* \end{bmatrix}\begin{bmatrix} \ddot{z} \\ \ddot{\vartheta} \end{bmatrix} + \begin{bmatrix} D_z^* & 0 \\ 0 & D_\vartheta^* \end{bmatrix}\begin{bmatrix} \dot{z} \\ \dot{\vartheta} \end{bmatrix} + \begin{bmatrix} -(W - B) \\ W r_{g_z} cos(\varphi) sin(\vartheta) \end{bmatrix} = \begin{bmatrix} \tau_z^* + w_{d_z}^* \\ \tau_\vartheta^* + w_{d_\vartheta}^* \end{bmatrix}$$

Studied Dynamics

$$\begin{bmatrix} M_z^* & 0 \\ 0 & M_\vartheta^* \end{bmatrix}\begin{bmatrix} \ddot{z} \\ \ddot{\vartheta} \end{bmatrix}+\begin{bmatrix} D_z^* & 0 \\ 0 & D_\vartheta^* \end{bmatrix}\begin{bmatrix} \dot{z} \\ \dot{\vartheta} \end{bmatrix}+\begin{bmatrix} -(W-B) \\ Wr_{g_z}cos(\varphi)sin(\vartheta) \end{bmatrix}=\begin{bmatrix} \tau_z^* + w_{d_z}^* \\ \tau_\vartheta^* + w_{d_\vartheta}^* \end{bmatrix}$$

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State Space Representation of the Studied Dynamics

$$\begin{bmatrix} \dot{\eta}_1 \\ \dot{\eta}_2 \end{bmatrix}=\begin{bmatrix} 0_{2\times2} & \mathbb{I}_2 \\ 0_{2\times2} & \frac{-D_r^*}{M_r^*} \end{bmatrix}\begin{bmatrix} \eta_1 \\ \eta_2 \end{bmatrix}-\begin{bmatrix} 0_{2\times1} \\ \frac{g_r^*}{M_r^*}-\frac{w_{d_r}^*}{M_r^*} \end{bmatrix}+\begin{bmatrix} 0_{2\times2} \\ \frac{1}{M_r^*} \end{bmatrix}\omega\tau_r^*$$

$\eta_1 = [z,\ \vartheta]^T$ and $\eta_2 = [\dot{z}, \dot{\vartheta}]^T$

Studied Dynamics

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$\mathcal{L}_1$ State Space Formulation

$$\begin{bmatrix} \dot{\eta}_1 \\ \dot{\eta}_2 \end{bmatrix}= A_m\begin{bmatrix} \eta_1 \\ \eta_2 \end{bmatrix}+\begin{bmatrix} 0_{2\times2} \\ \frac{1}{M_r^*} \end{bmatrix}\left(\omega u_a + \theta(t)\|\eta(t)\|_{\mathcal{L}_\infty} + \sigma(t)\right)$$

$$y = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}\begin{bmatrix} \eta_1 \\ \eta_2 \end{bmatrix}=\begin{bmatrix} z \\ \vartheta \end{bmatrix}$$

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[redacted]

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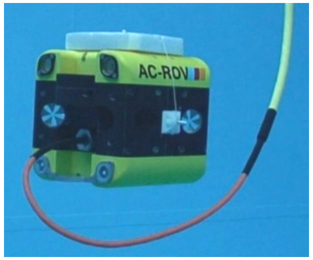
Experiments

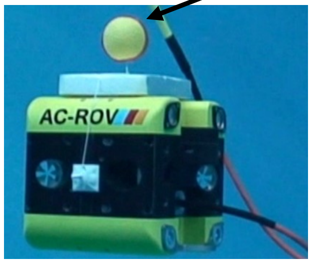
Experimental Scenarios

Scenario1
nominal conditions



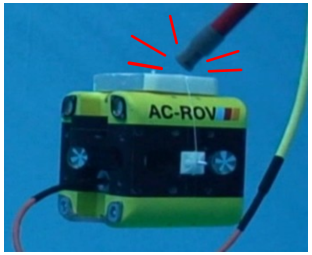
Scenario 2
robustness towards uncertainties

added buoyancy



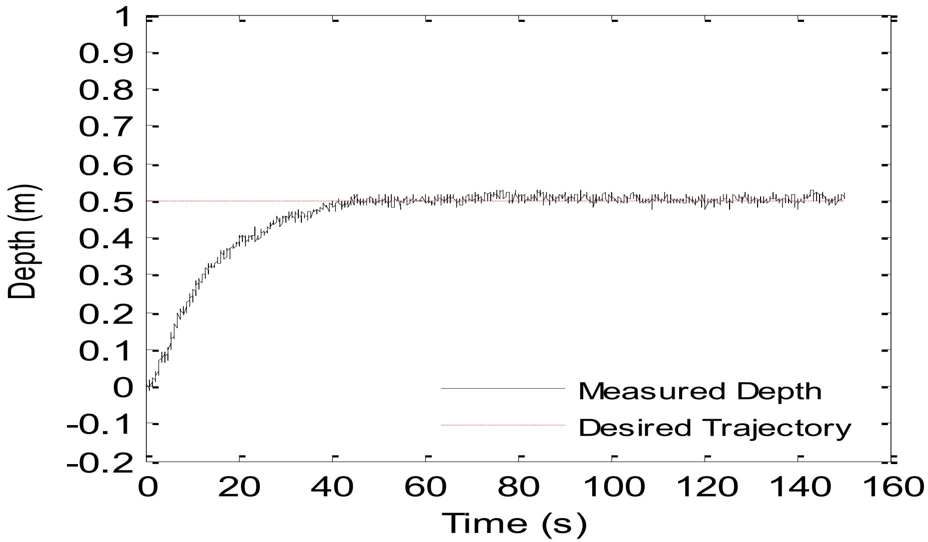
Scenario 3
external disturbances rejection

mechanical impact

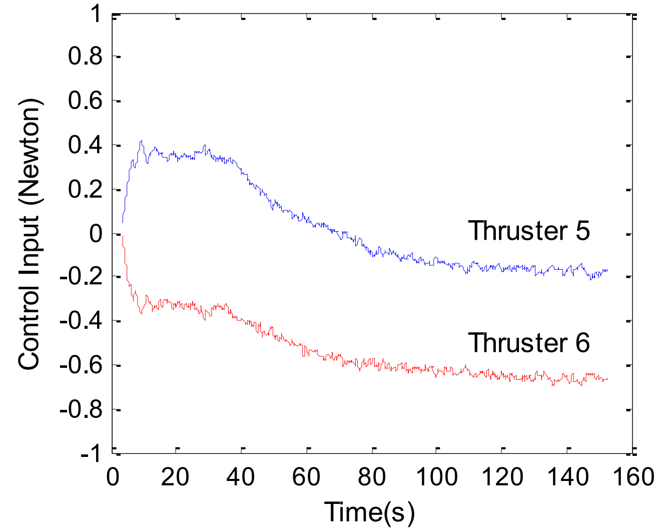


Scenario 1 Nominal Conditions

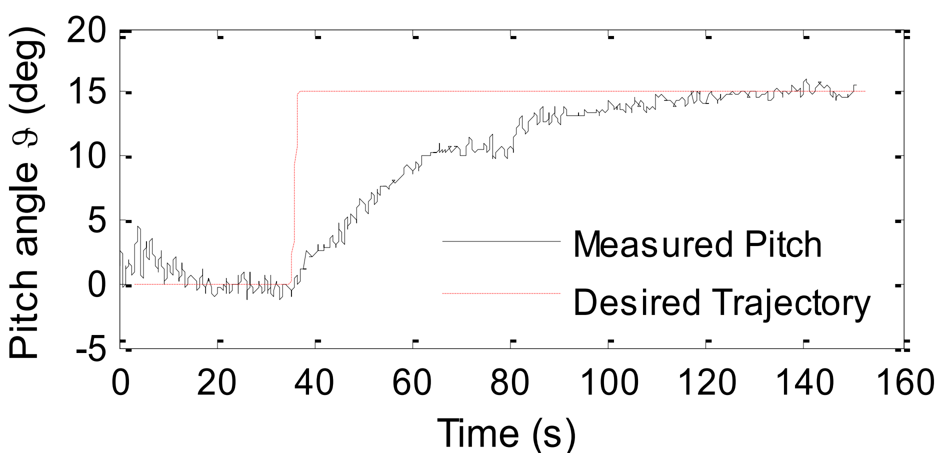
Depth (z)



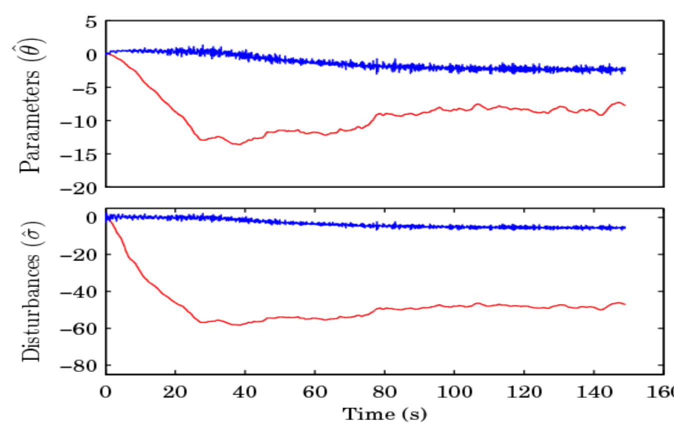
Control inputs



Pitch ϑ

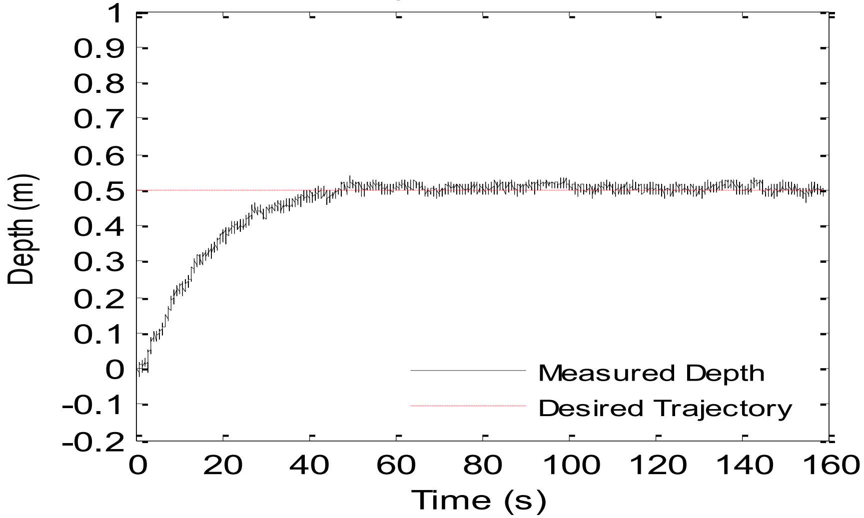


Estimated parameters and disturbances

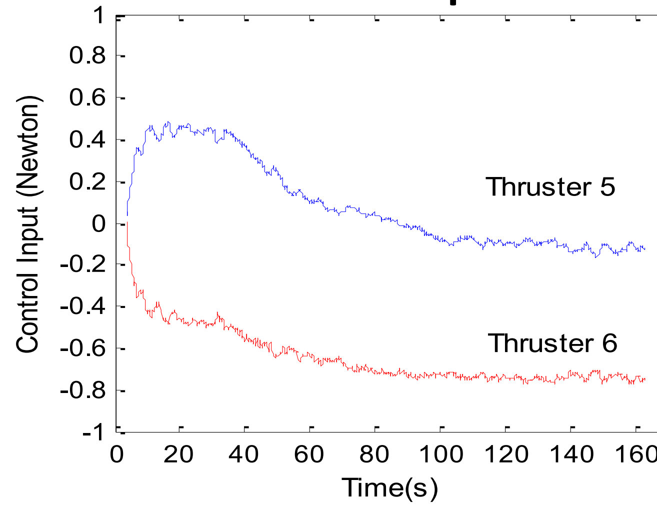


Scenario 2 Robustness Towards Parameter Uncertainties (Buoyancy Increase 32%)

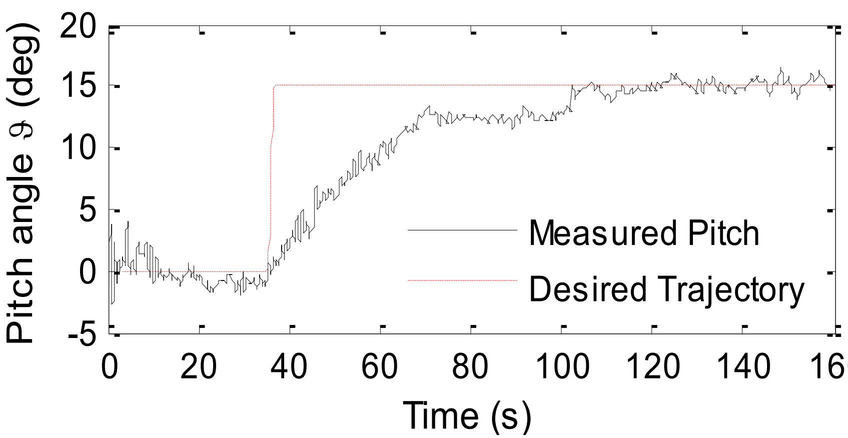
Depth (z)



Control inputs



Pitch (ϑ)



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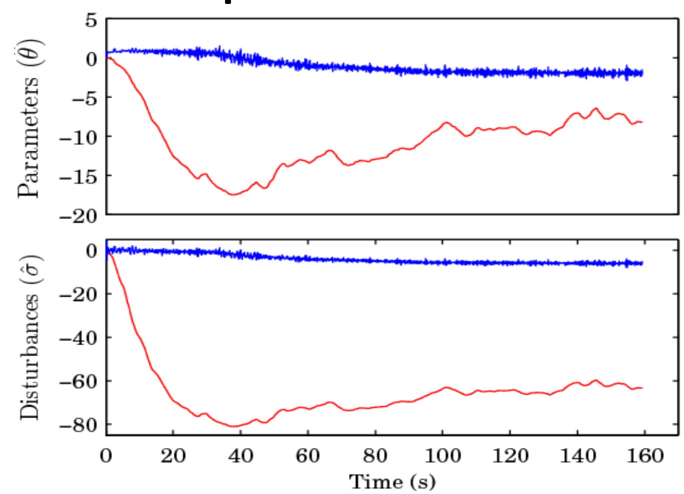
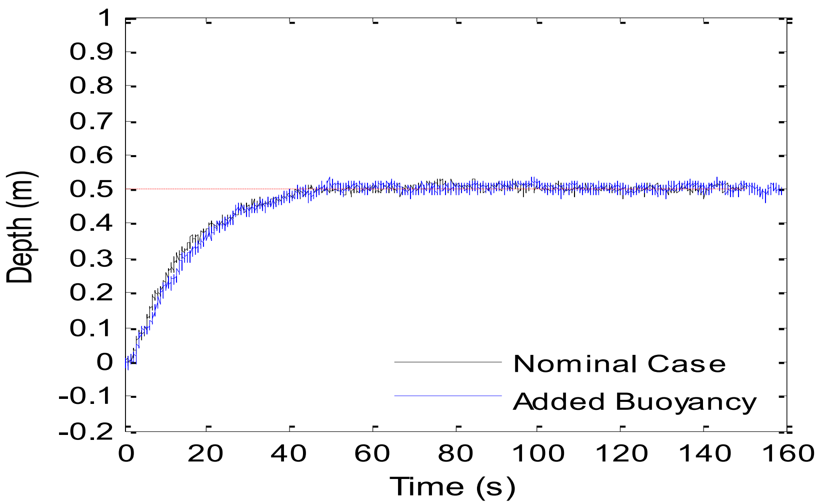


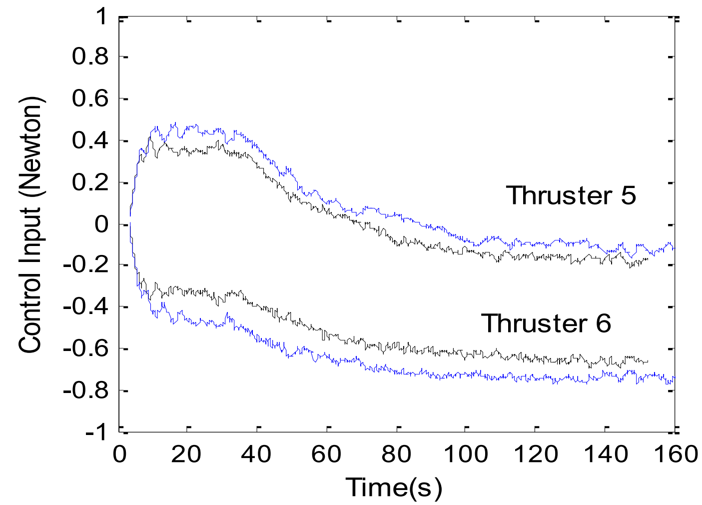
Scenarios 1 and 2 overlapped

Nominal case
Added Buoyancy

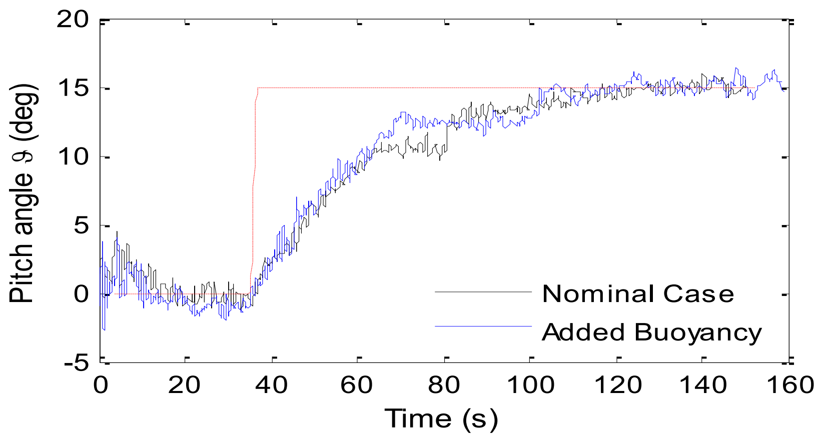
Depth (z)



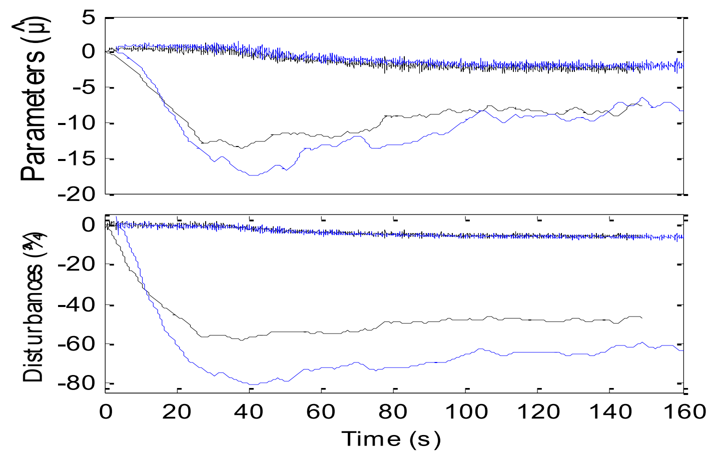
Control inputs



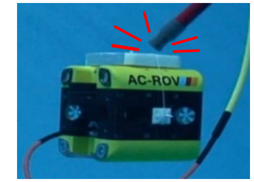
Pitch (ϑ)



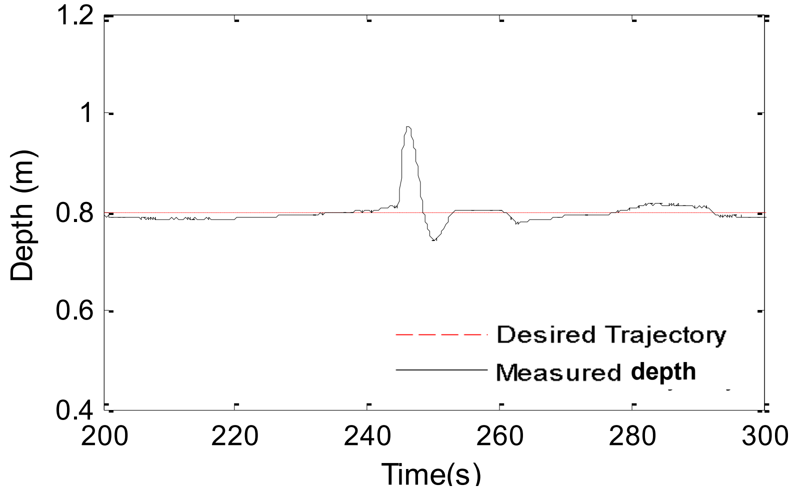
Estimated parameters and disturbances



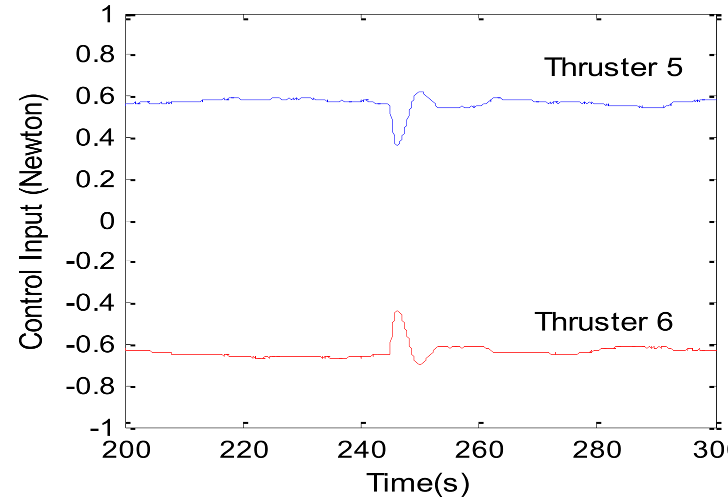
Scenario 3 External Disturbance Rejection (Punctual Disturbance)



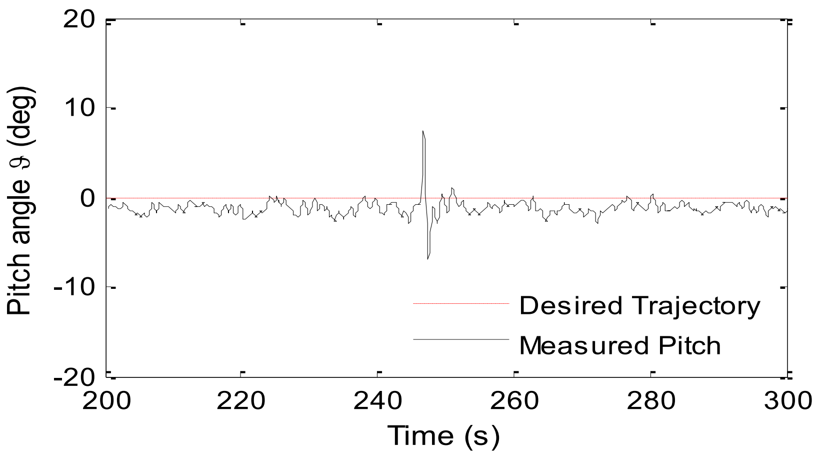
Depth (z)



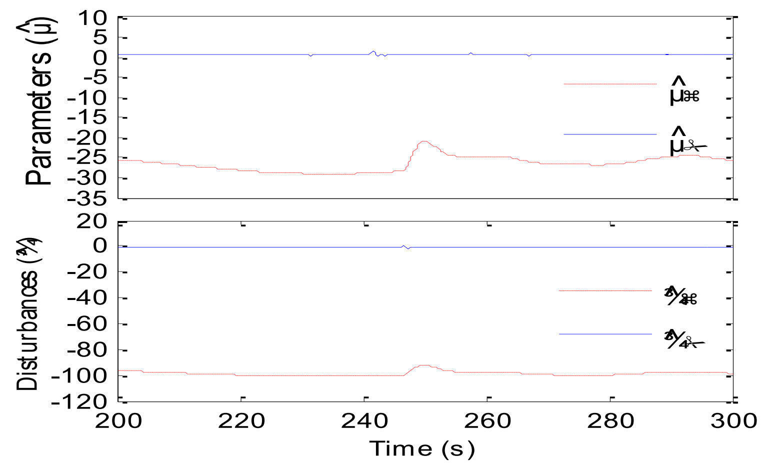
Control inputs



Pitch (ϑ)



Estimated parameters and disturbances

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tecnalia
$\mathcal{L}_1$ adaptive depth control of an underwater vehicle in presence of uncertainties and disturbances
Divine Maalouf, Ahmed Chemori, Vincent Creuze, and Olivier Tempier
LIRMM, CNRS / Université Montpellier 2
http://www.lirmm.fr/~creuze/UWR.htm

Conclusion

Problem: Control of an underwater vehicle for trajectory tracking in presence of parameter uncertainties and external disturbances

Proposed Solution: $\mathcal{L}_1$ adaptive controller

Difficulties inherent to the system:

- High nonlinearities in the system's dynamics
- Variation of the model parameters
- Presence of external disturbances

Results: Experimental validation through various scenarios

Advantages of the proposed solution :

- Robustness and adaptation decoupled
- Usage of high adaptation gains
- Robustness towards uncertainties
- External disturbances rejection
- No a priori knowledge of the parameters is needed