27th November 2023

Thesis Defense

Analysis and Control of Autonomous Underwater Vehicles with Reconfigurable vectoring thrust

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Definition Underactuated AUV

Underactuated System:

Fewer actuators (inputs) than DOFs

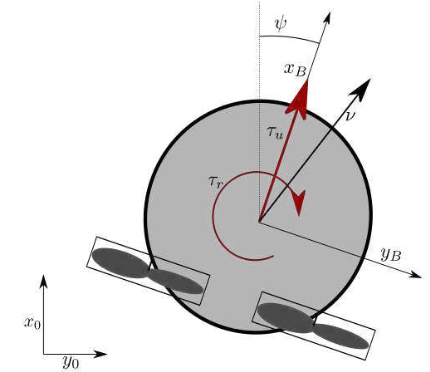


Figure 3: Example of underactuated system
The hovercraft: 2 actuated DOFs, 3 DOFs space

Underactuated AUV (w.r.t. a task):

Fewer actuators (inputs) than DOFs **required in the task**

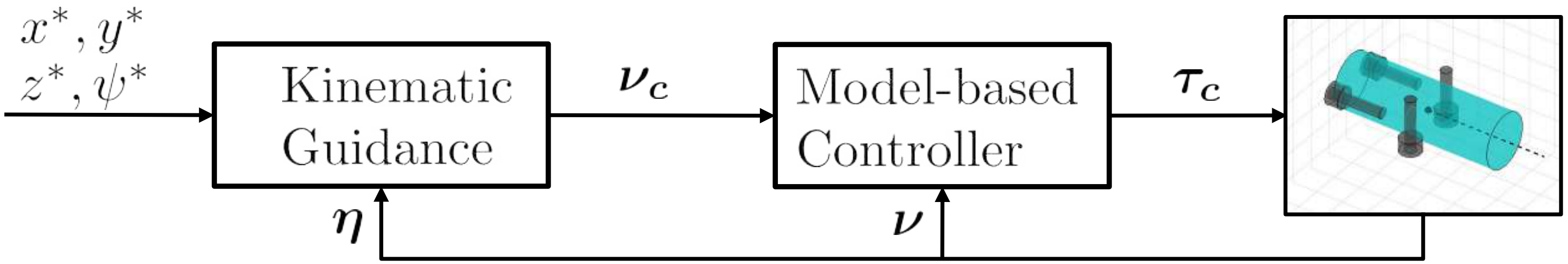
Ill-actuated AUV (w.r.t. a task):

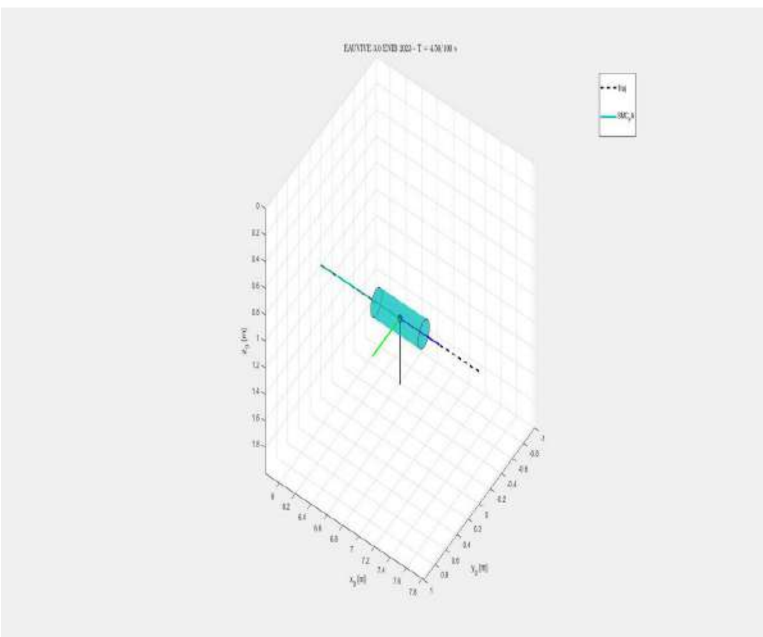
Same number of actuators as DOFs required in the task but they **don't match**

Figure 4: Remus100 : Actuated in surge, pitch and yaw, used on task requiring 3 translations (Credit: WOI)

Guidance Principle Required

Kinematic Guidance Principle





Video 1: Expected behavior on the seabed scanning task

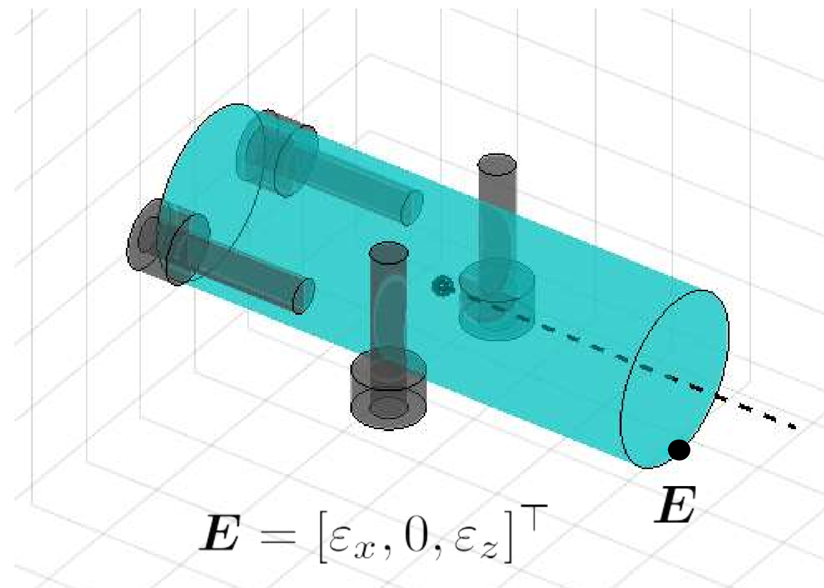


Figure 6: RSM with a Virtual Tracking Point E

[Alonge, 2001]
[Slotine et Li, 1991]

Kinematic Guidance: Virtual Reference Point

Introduce new kinematic coupling terms

Enhance natural stability in attitude

Kinematic Model Update:

$$\boldsymbol{T} = \begin{bmatrix} \mathbb{I}_3 & \boldsymbol{S} \\ \boldsymbol{0}_{3\times 3} & \mathbb{I}_3 \end{bmatrix}$$

$$\boldsymbol{E} = [\varepsilon_x, 0, \varepsilon_z]^\top$$

$$\dot{\boldsymbol{\eta}} = \boldsymbol{J}(\boldsymbol{\eta})\boldsymbol{\nu} \longrightarrow \dot{\boldsymbol{\eta}}_{\boldsymbol{E}} = \boldsymbol{J}(\boldsymbol{\eta})\boldsymbol{T}\boldsymbol{\nu}$$

$$\boldsymbol{S} = \begin{bmatrix} 0 & \varepsilon_z & 0 \\ -\varepsilon_z & 0 & \varepsilon_x \\ 0 & -\varepsilon_x & 0 \end{bmatrix}$$

New linear speed relations in the mobile frame:

$$\boldsymbol{\nu}_{\boldsymbol{E}} = \boldsymbol{T}\boldsymbol{\nu}$$

$$u_E = u + \varepsilon_z q$$

$$v_E = v - \varepsilon_z p + \varepsilon_x r$$

$$w_E = w - \varepsilon_x q$$

New angular speed relations:

Roll:

$$p = \frac{-1}{\varepsilon_z}(\boldsymbol{v}_{\boldsymbol{E}} - v - \varepsilon_x r)$$

Yaw:

$$r = \frac{1}{\varepsilon_x}(\boldsymbol{v}_{\boldsymbol{E}} - v + \varepsilon_z p)$$

[Berge, 1999]

Introduction of the Handy Matrix to reproduce the model manipulations

$$\dot{\boldsymbol{\eta}}_E = \boldsymbol{J}(\boldsymbol{\eta})\boldsymbol{T}\boldsymbol{\nu} \xrightarrow{v_c = 0} \boldsymbol{\nu}_c = \mathcal{H}\boldsymbol{T}^{-1}\boldsymbol{J}(\boldsymbol{\eta})^{-1}\boldsymbol{\Lambda}(\boldsymbol{\eta}^*, \boldsymbol{e}_{\eta})$$

Roll compensation:

$$p_c = \frac{-1}{\varepsilon_z}(v_E^* - \varepsilon_x r)$$

$$\mathcal{H}_p = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & -1/\varepsilon_z & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Yaw compensation:

$$r_c = \frac{1}{\varepsilon_x}(v_E^* + \varepsilon_z p)$$

$$\mathcal{H}_r = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1/\varepsilon_x & 0 & 0 & 0 & 1 \end{bmatrix}$$

The Handy Matrix creates the expected Guidance mechanism

[Degorre et al., 2022]
[Degorre et al., 2023a]

Kinematic Guidance: Handy $\mathcal{H}$ Matrix

Construction of the Handy Matrix for roll compensation:

$$p_c = \frac{-1}{\varepsilon_z}\left(v_E^* - \varepsilon_x r\right)$$

$$\boldsymbol{h_{O_B}} = [1, 0, 1, 1, 0, 1]^\top$$

$$\boldsymbol{h_E} = [1, 1, 1, 0, 0, 1]^\top$$

$$\boldsymbol{\Sigma} = \begin{bmatrix} 0 & -1/\varepsilon_z & 0 \\ 1/\varepsilon_z & 0 & -1/\varepsilon_x \\ 0 & 1/\varepsilon_x & 0 \end{bmatrix}$$

$$\mathcal{H}_p = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & -1/\varepsilon_z & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Design Rules:

1. $\boldsymbol{E}$ must be different from $\boldsymbol{O_B}$
2. Can only compensate translations with rotations.
3. Cannot compensate a translation on one axis with a rotation around the same axis.

Algorithm 1 Calculation of the Handy matrix $\mathcal{H}$

```
H ← I_6
e ← [ε_x ε_y ε_z]^T
ϵ ← [0 0 0]^T
for k = 1 : 3
    if e(k) ≠ 0
        ϵ(k) ← 1/e(k)
Σ ← S(ϵ)
for i = 3 : 6
    if h_OB(i) = 1 and h_E(i) = 0
        for j = 1 : 3
            if h_E(j) = 1 and h_OB(j) = 0 and j ≠ i − 3
                H(i, j) ← Σ(i − 3, j)
                H(j, :) ← 0
```

Kinematic Guidance: Handy$\mathcal{H}$Matrix

Consequences on the closed-loop system – Roll compensation

$$\dot{\boldsymbol{\eta}}_{\boldsymbol{E}} = \boldsymbol{J}(\boldsymbol{\eta})\boldsymbol{T}\boldsymbol{\nu}_{\boldsymbol{c}}$$

$$\boldsymbol{\nu}_{\boldsymbol{c}} = \mathcal{H}_p \boldsymbol{T}^{-1}\boldsymbol{J}(\boldsymbol{\eta})^{-1}\boldsymbol{\Lambda}(\boldsymbol{\eta}^*, \boldsymbol{e}_{\boldsymbol{\eta}})$$

$$\boldsymbol{J}(\boldsymbol{\eta}) = \begin{bmatrix} \boldsymbol{J_1}(\boldsymbol{\eta}) & \mathbf{0}_{3\times3} \\ \mathbf{0}_{3\times3} & \boldsymbol{J_2}(\boldsymbol{\eta}) \end{bmatrix}$$

$$\dot{\boldsymbol{\eta}}_{\boldsymbol{E}} = \boldsymbol{J}(\boldsymbol{\eta})\boldsymbol{T}\mathcal{H}_{\boldsymbol{p}}\boldsymbol{T}^{-1}\boldsymbol{J}(\boldsymbol{\eta})^{-1}\boldsymbol{\Lambda}(\boldsymbol{\eta}^*, \boldsymbol{e}_{\boldsymbol{\eta}})$$

$$\boldsymbol{\Lambda}(\boldsymbol{\eta}^*, \boldsymbol{e}_{\boldsymbol{\eta}}) = \begin{bmatrix} \dot{x}^* + \mathrm{PI}(e_x) \\ \dot{y}^* + \mathrm{PI}(e_y) \\ \dot{z}^* + \mathrm{PI}(e_z) \\ 0 \\ 0 \\ \dot{\psi}^* + \mathrm{PI}(e_\psi) \end{bmatrix}$$

$$\boldsymbol{T}\mathcal{H}_{\boldsymbol{p}}\boldsymbol{T}^{-1} = \begin{bmatrix} \mathbf{1} & 0 & 0 & 0 & 0 & 0 \\ 0 & \mathbf{1} & 0 & 0 & 0 & 0 \\ 0 & 0 & \mathbf{1} & 0 & 0 & 0 \\ 0 & 0 & -1/\varepsilon_z & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & \mathbf{1} \end{bmatrix}$$

$$\begin{aligned} \dot{x}_E &= \dot{x}^* + \mathrm{PI}(e_x) \\ \dot{y}_E &= \dot{y}^* + \mathrm{PI}(e_y) \\ \dot{z}_E &= \dot{z}^* + \mathrm{PI}(e_z) \\ \dot{\psi} &= \dot{\psi}^* + \mathrm{PI}(e_\psi) \end{aligned}$$

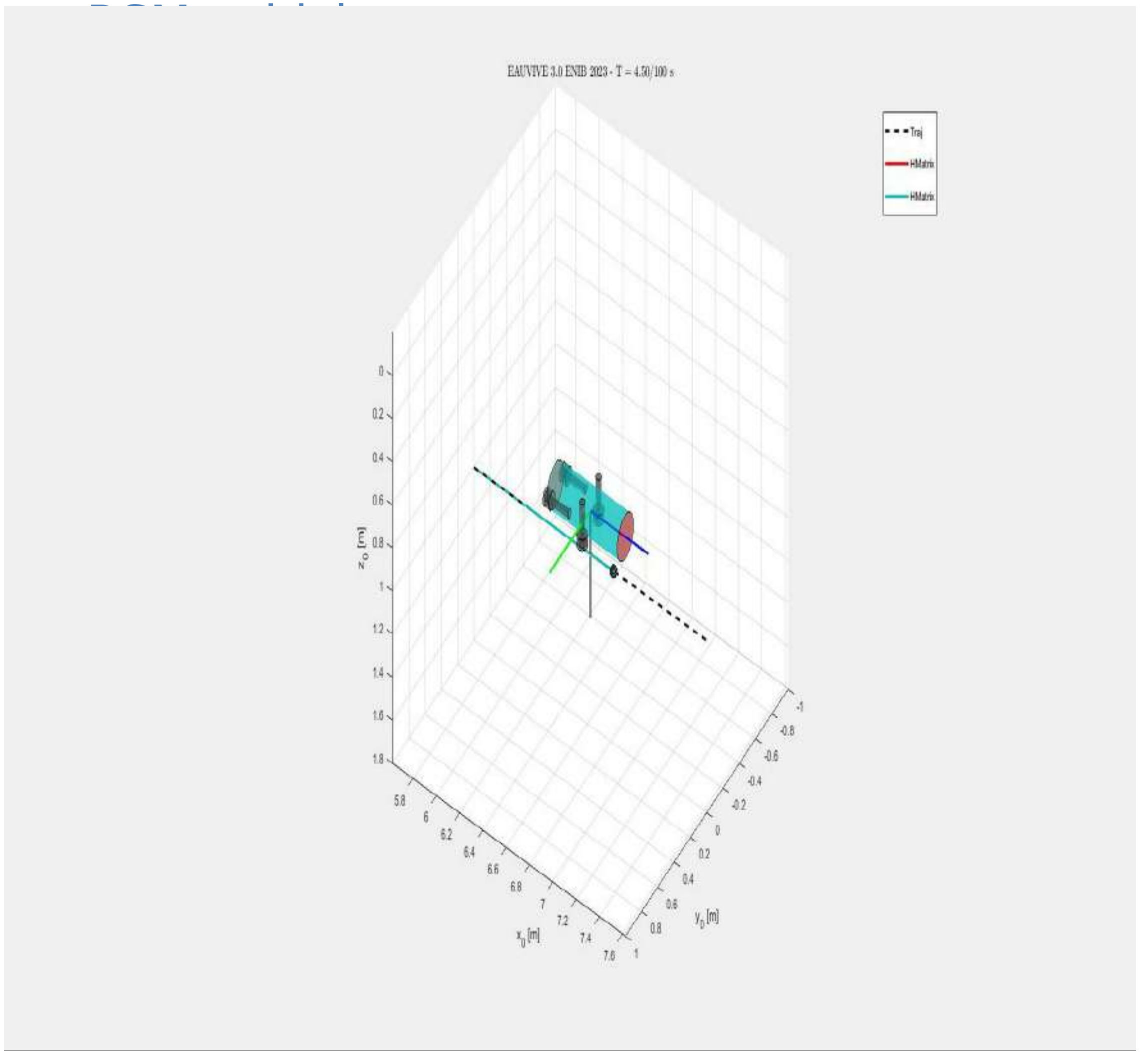
$$\dot{\phi} = f(\mathrm{PI}(e_x), \mathrm{PI}(e_y), \mathrm{PI}(e_z))$$

[Degorre et al., 2023b]

Kinematic Guidance: Handy $\mathcal{H}$ Matrix

Application 1: Seabed Scanning with the

$$\boldsymbol{E} = [\varepsilon_x, 0, \varepsilon_z]^\top \quad \varepsilon_x = \varepsilon_z$$



Video 2: Comparison of the two compensation solutions

Blue vehicle
- Roll compensation
- Yaw is controlled

Red vehicle
- Yaw compensation
- (Roll is controlled)

Both solutions have a perfect position tracking

The red vehicle cannot meet the heading constraint

Kinematic Guidance Principle

Partial Conclusion

- Easily generalizable thanks to the algorithm
- Allows mixing several types of actuators
- Can give several compensation solutions
- The behaviour of the VRP can be tailored
- Good robustness to external disturbance
- The DOF used for compensation is not controlled

Associated Communications

- Degorre L., Chocron O. and Delaleau E. – *A new general approach for model-based control of underactuated AUV based on kinematic coupling.* – IROS 2022

- Degorre L., Fossen T.I., Chocron O., Delaleau E. – *A Model-Based Kinematic Guidance Method for Control of Underactuated Autonomous Underwater Vehicles.* – CEP – Under Review

- Degorre L., Fossen T.I., Chocron O., Delaleau E. – *A Virtual Reference Point Kinematic Guidance Law for 3-D Path-Following of Autonomous Underwater Vehicles.* – JOE – Under Review

Flatness-based control

Introduction to flatness – The Fully-Actuated AUV

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

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

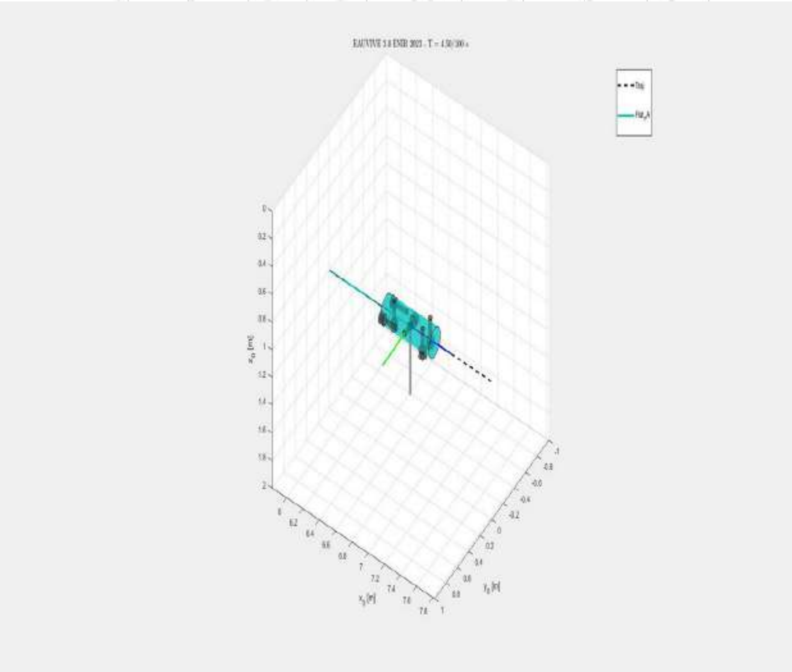
$$\Downarrow \quad \boldsymbol{z} = \boldsymbol{\eta} = [x, y, z, \phi, \theta, \psi]^\top$$

$$\boldsymbol{\nu} = \boldsymbol{J}(\boldsymbol{\eta})^{-1}\dot{\boldsymbol{\eta}}$$

$$\boldsymbol{\tau} = \widehat{\boldsymbol{M}}(\boldsymbol{\eta})\ddot{\boldsymbol{\eta}} + \widehat{\boldsymbol{C}}(\boldsymbol{\eta}, \dot{\boldsymbol{\eta}})\dot{\boldsymbol{\eta}} + \widehat{\boldsymbol{D}}(\boldsymbol{\eta}, \dot{\boldsymbol{\eta}})\dot{\boldsymbol{\eta}} + \boldsymbol{g}(\boldsymbol{\eta})$$

$$\Downarrow$$

$$\boldsymbol{\tau} = \widehat{\boldsymbol{M}}(\boldsymbol{\eta}^*)(\ddot{\boldsymbol{\eta}}^* + \mathbf{PID}(\boldsymbol{e}_{\boldsymbol{\eta}})) + \widehat{\boldsymbol{C}}(\boldsymbol{\eta}^*, \dot{\boldsymbol{\eta}}^*)\dot{\boldsymbol{\eta}}^* + \widehat{\boldsymbol{D}}(\boldsymbol{\eta}^*, \dot{\boldsymbol{\eta}}^*)\dot{\boldsymbol{\eta}}^* + \boldsymbol{g}(\boldsymbol{\eta}^*)$$



Video 3: Fully Actuated Flatness-based controller

[Fliess et al., 1992]
[Rigatos et al., 2017]

Flatness-based control

The underactuated Surface Vessel

Control the position in the horizontal plane with the surge force and yaw moment

Not Flat – At least 1 defect:

$$F(\psi, \dot{\psi}, \ddot{\psi}, ...) = 0$$

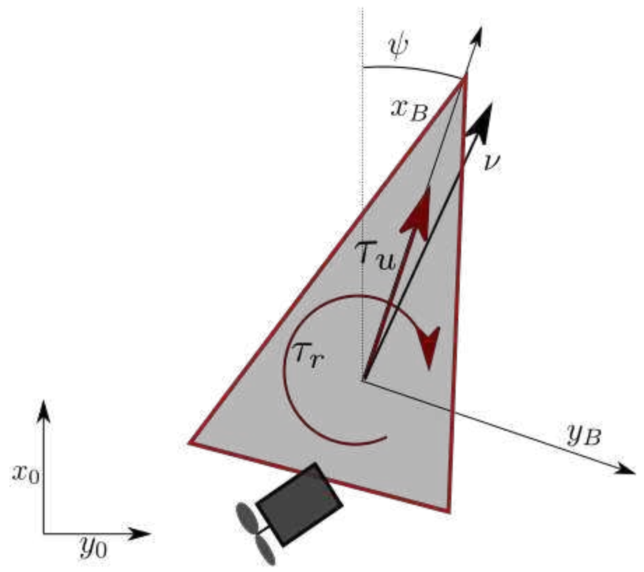


Figure 13: Generic Surface Vessel with vector thruster

Flat – Simplified model, circular shape, homogeneous mass distribution

$$\boldsymbol{\tau} = [\tau_u, 0, \tau_r]^\top$$

$$\boldsymbol{z} = [x, y]^\top$$

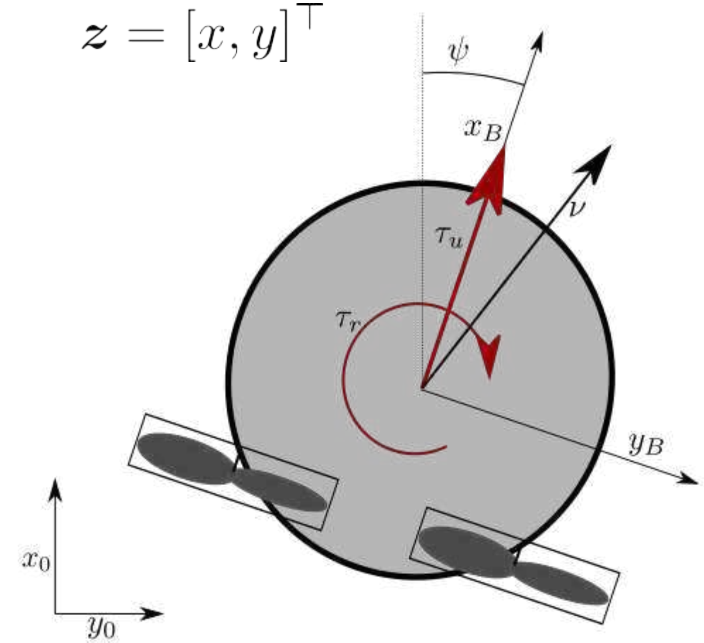


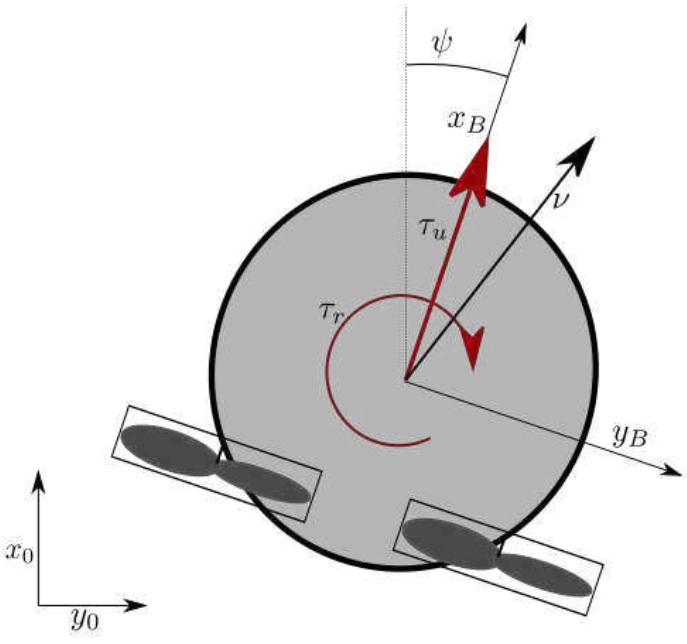
Figure 14: Simplified Hovercraft with two rear propellers

[Sira-Ramirez and Agrawal, 2004]

Flatness-based control

The underactuated Surface Vessel: Special case of the Hovercraft

Simplified model is flat with the flat output $\boldsymbol{z} = [x, y]^\top$



$$
\begin{aligned}
\dot{x} &= u\cos\psi - v\sin\psi \\
\dot{y} &= u\sin\psi + v\cos\psi \\
\dot{\psi} &= r \\
\dot{u} &= \tau_u + vr + \beta u \\
\dot{v} &= -ur + \beta v \\
\dot{r} &= \tau_r + \gamma r
\end{aligned}
$$

$$\boldsymbol{\tau} = [\tau_u, 0, \tau_r]^\top$$

$$\boldsymbol{z} = [x, y]^\top$$

Equations of Flatness:

$$\psi = \operatorname{atan}\left(\frac{\ddot{y} - \beta\dot{y}}{\ddot{x} - \beta\dot{x}}\right)$$

$$\tau_u = \sqrt{(\ddot{x} - \beta\dot{x})^2 + (\ddot{y} - \beta\dot{y})^2}$$

$$\tau_r = f(x, y, \ldots, x^{(4)}, y^{(4)})$$

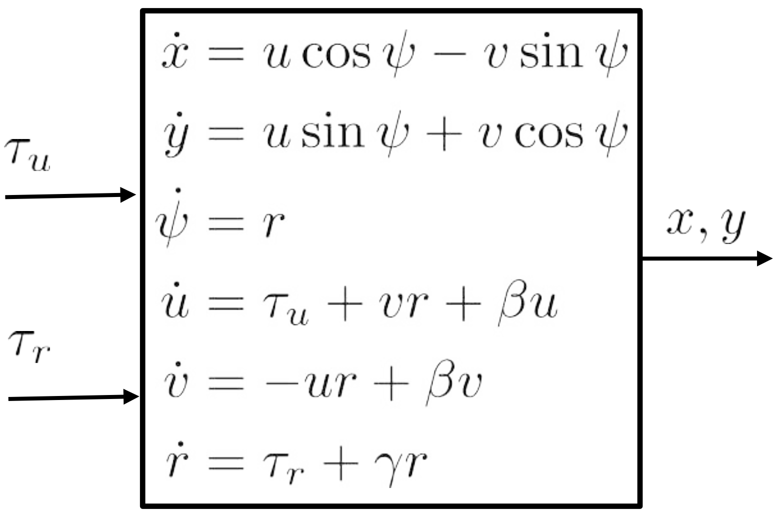
[Sira-Ramirez and Agrawal, 2004]

[Rigatos, 2015]

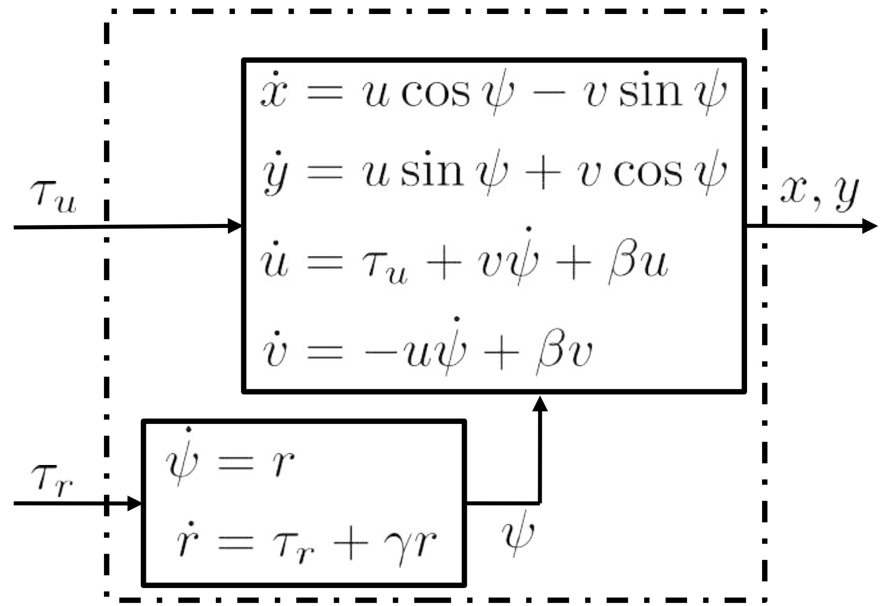
Flatness-based control

Control of the Hovercraft

Change of input



Simplified model of the Hovercraft

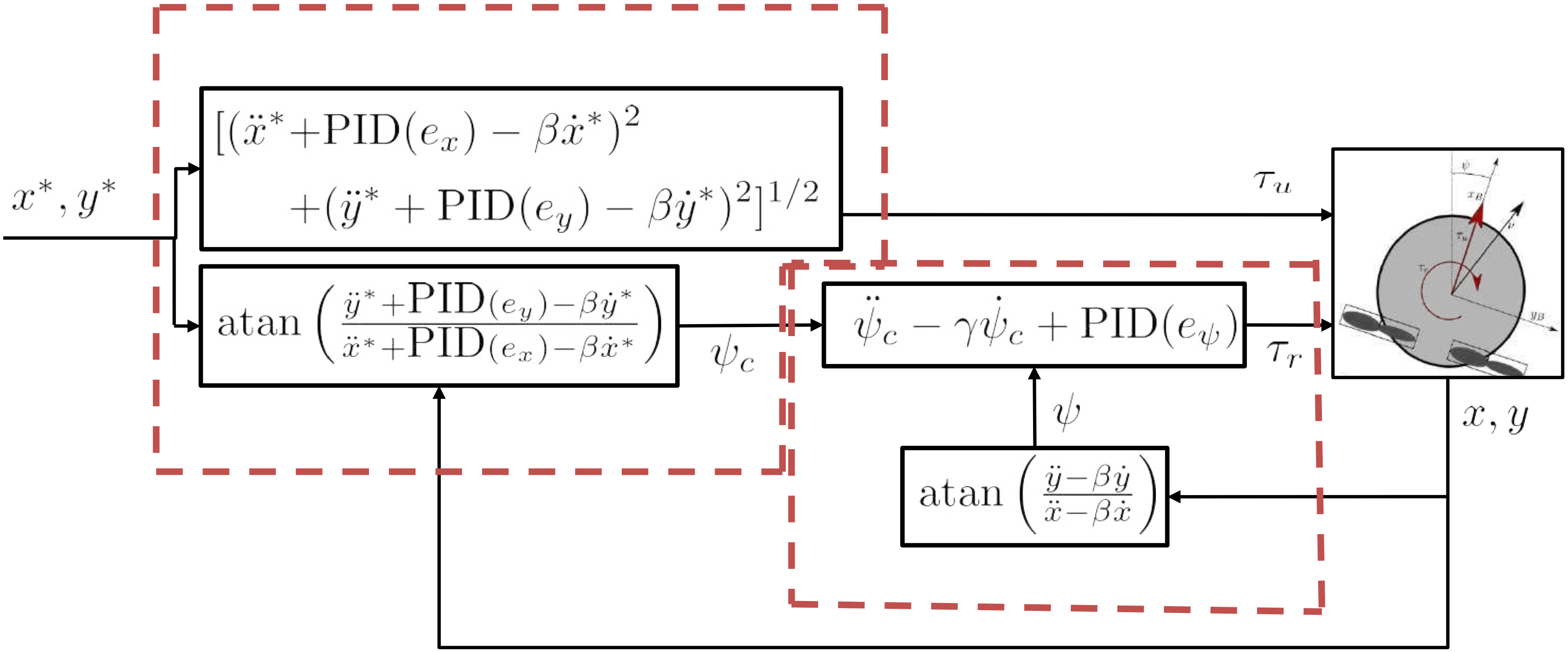


Two subsystems – Unidirectional coupling

Flatness-based control

Control of the Hovercraft

Complete controller



$$\mathrm{PID}(e_x) = k_{d,x}\dot{e}_x + k_{p,x}e_x + k_{i,x}\int_0^t e_x(\sigma)d\sigma$$

Flatness-based control

Application 1 : Trajectory tracking of the Hovercraft

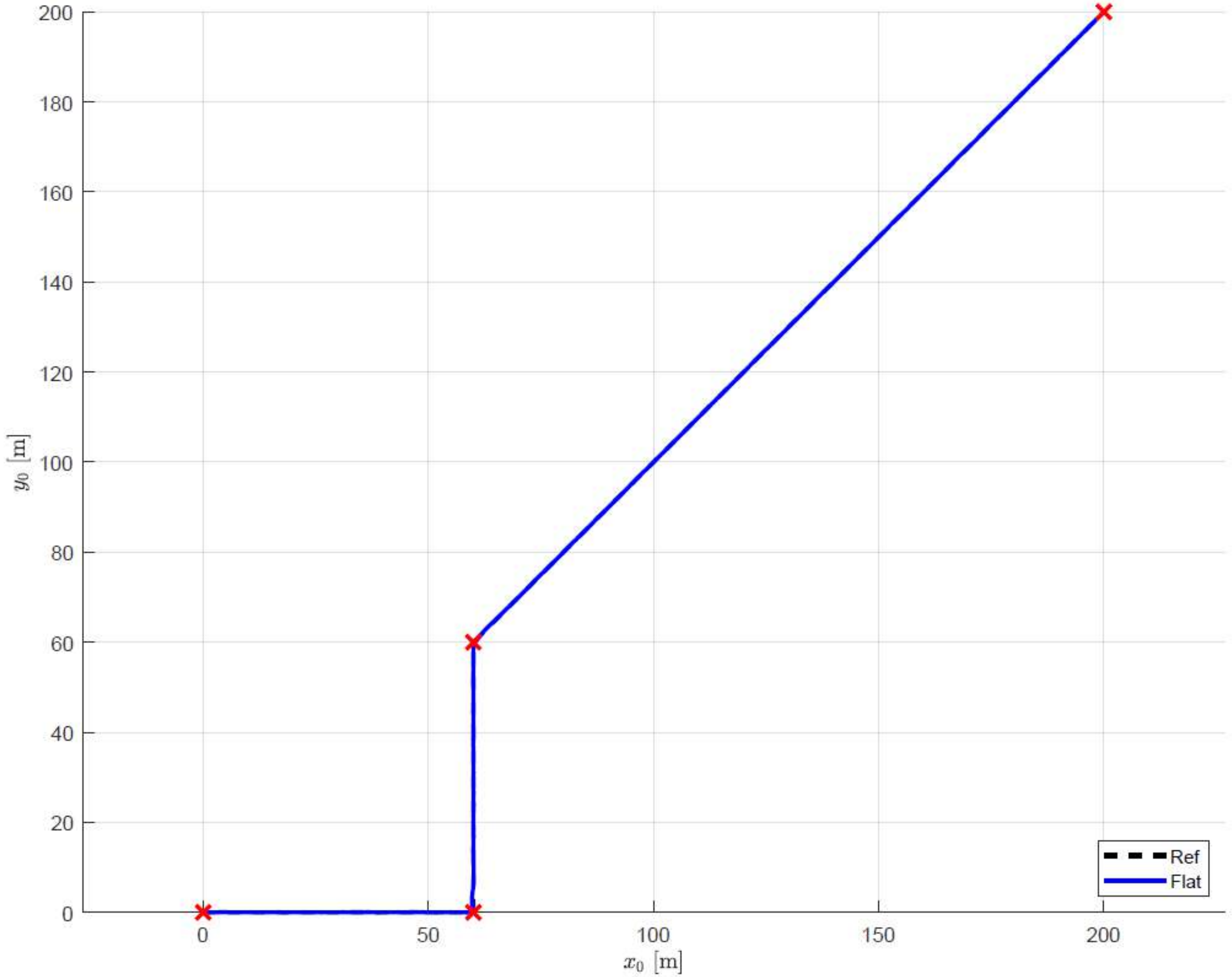


Figure 16: Trajectory Tracking of the Hovercraft using the Flatness-based controller with measurement noise and a -0,75 m/s current on x_0

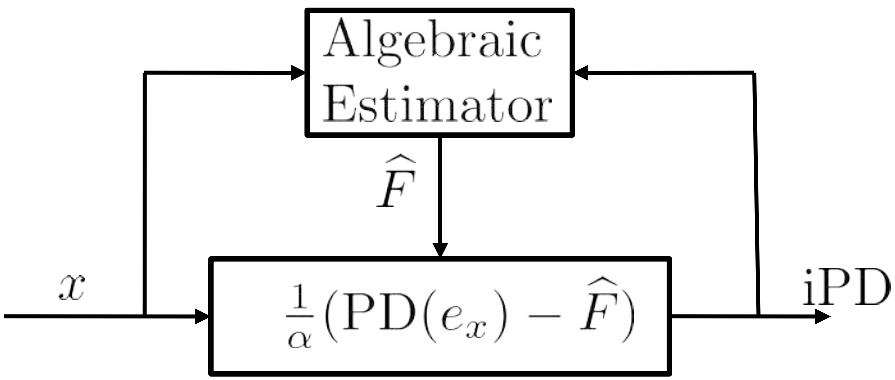
Flatness-based control

Association with iPD

Increases robustness of the controller
Facilitates application to the Surface Vessel

Ultra-local model second order:

$$\ddot{x} = \alpha u + F$$



Integration to the Flatnes-based controller:

$$\tau_u = [(\ddot{x}^* + \mathrm{iPD}(e_x, \widehat{F}_x) - \beta \dot{x}^*)^2 + (\ddot{y}^* + \mathrm{iPD}(e_y, \widehat{F}_y) - \beta \dot{y}^*)^2]^{1/2}$$

$$\psi_c = \mathrm{atan}\left(\frac{\ddot{y}^* + \mathrm{iPD}(e_y, \widehat{F}_y) - \beta \dot{y}^*}{\ddot{x}^* + \mathrm{iPD}(e_x, \widehat{F}_x) - \beta \dot{x}^*}\right)$$

[Fliess and Join, 2009]

Flatness-based control

Application 2: Trajectory Tracking of the Surface Vessel with Flatne

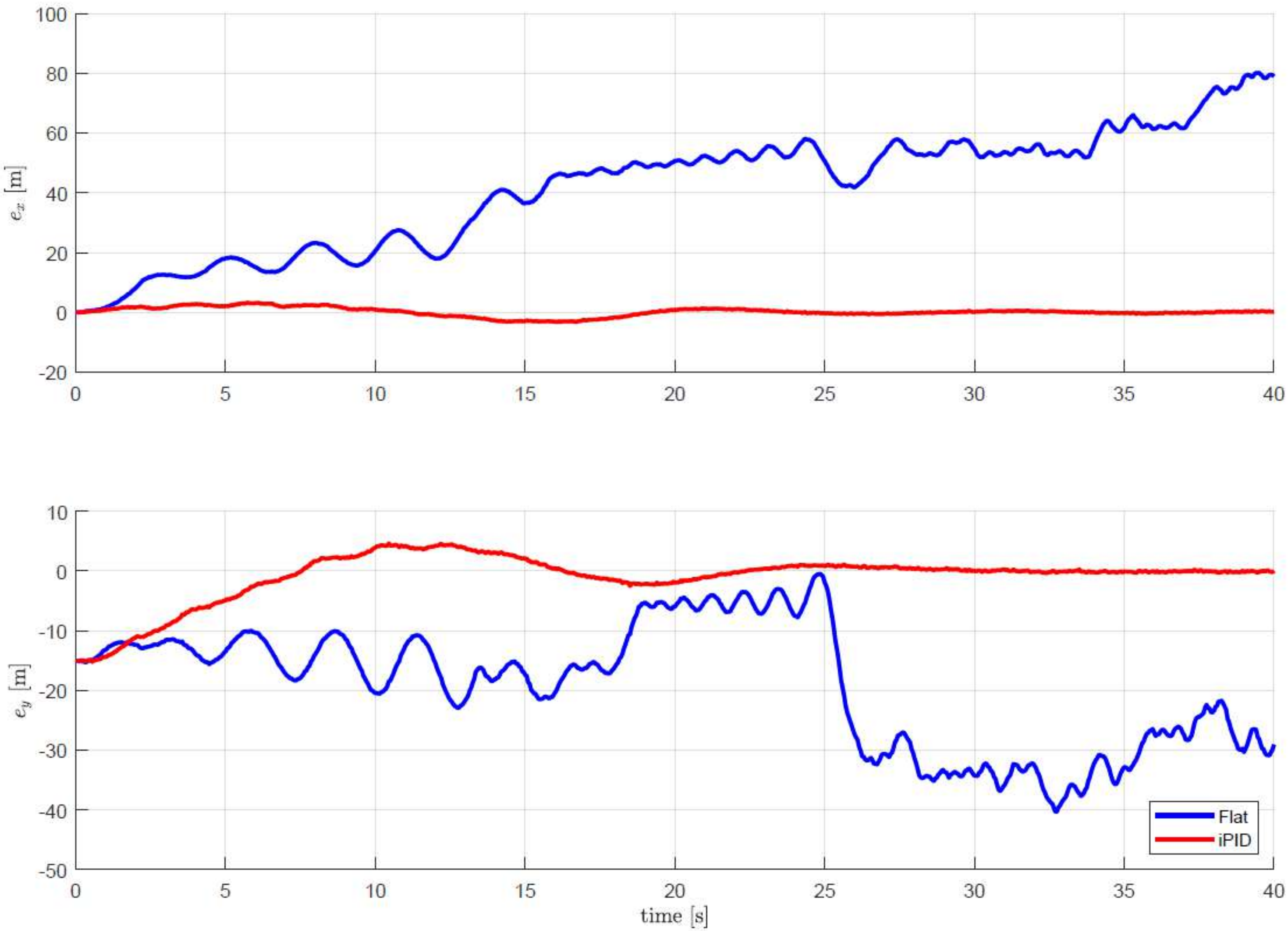


Figure 17: Tracking error comparison, Flatness based controller and iPD applied to a generic surface vessel with 15m initial error on y_0

Flatness-based control

Partial Conclusion

- Flatness-based controller developed for the hovercraft with great results
- Controller includes a guidance principle
- Can be applied to surface vessels
- Robustness can be increased with iPD

Work In Progress

- Degorre L., Chocron O. and Delaleau E. – *Flatness-based control of the Hovercraft* –Transaction on Automatic Control
- Degorre L., Fliess M., Join C., Chocron O., Delaleau E. – *Association of Flatness-based control and iPID for control of surface vessels* – Journal to be determined

Reconfiguration ring

Novel vectoring thrust concept without coupling

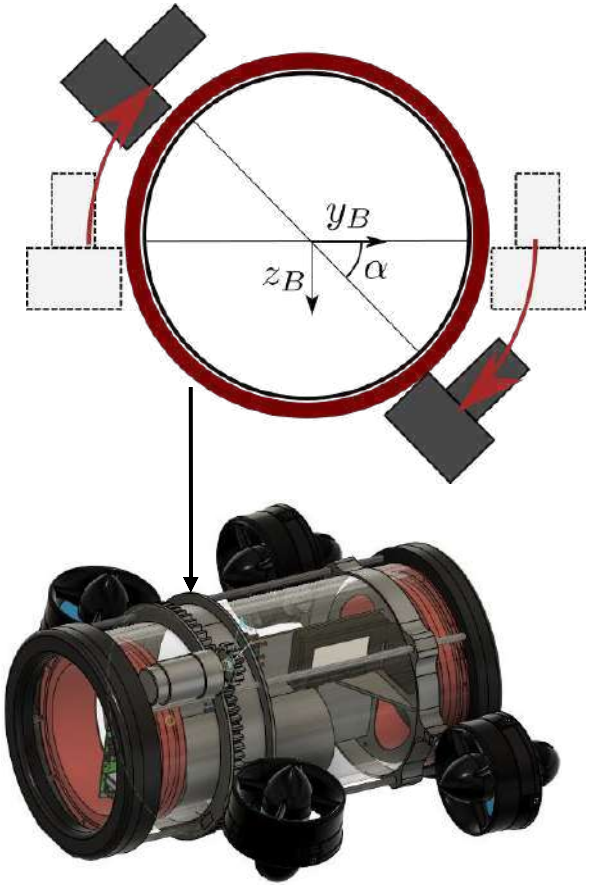


Figure 21: PlaSMAR Configuration 1 - Force
Actuated DOFs : Surge, Sway, Heave, Roll, Yaw

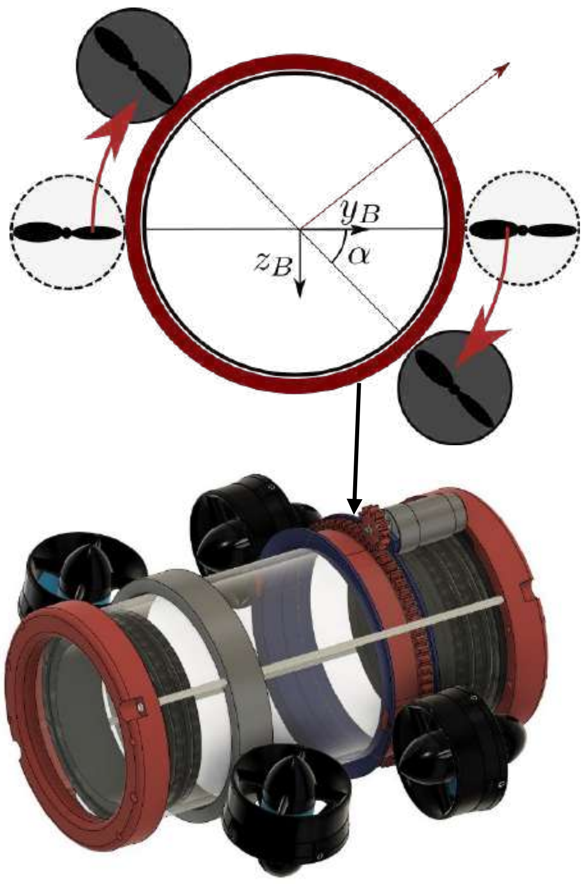
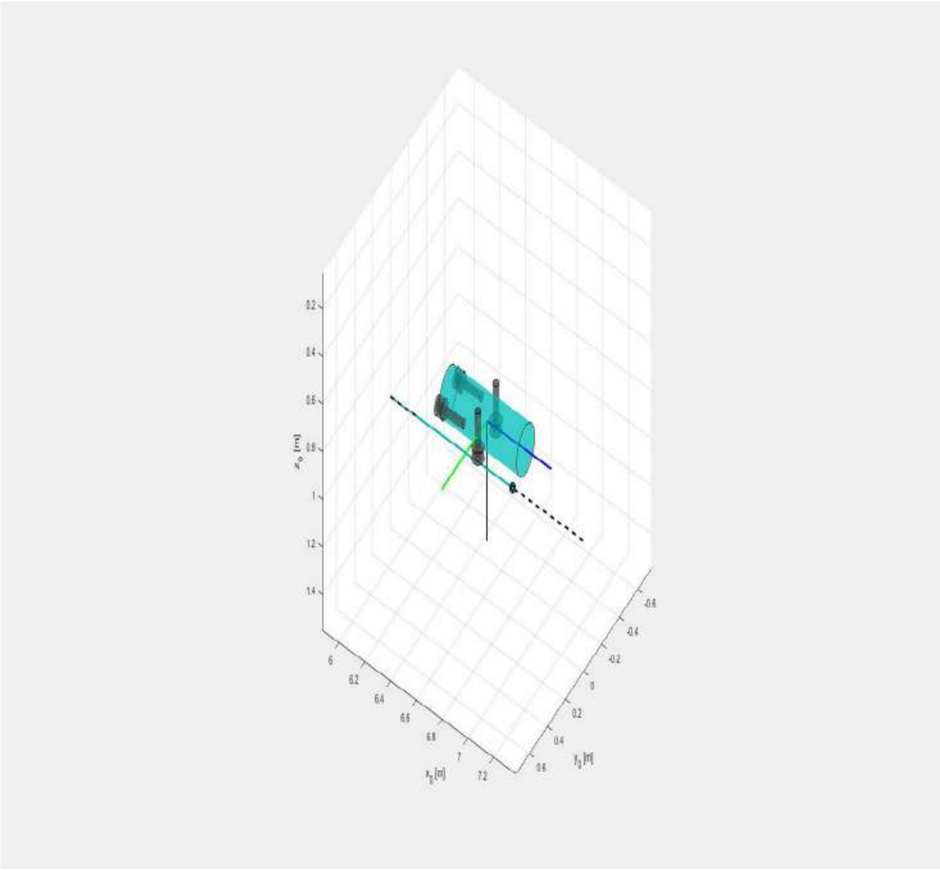


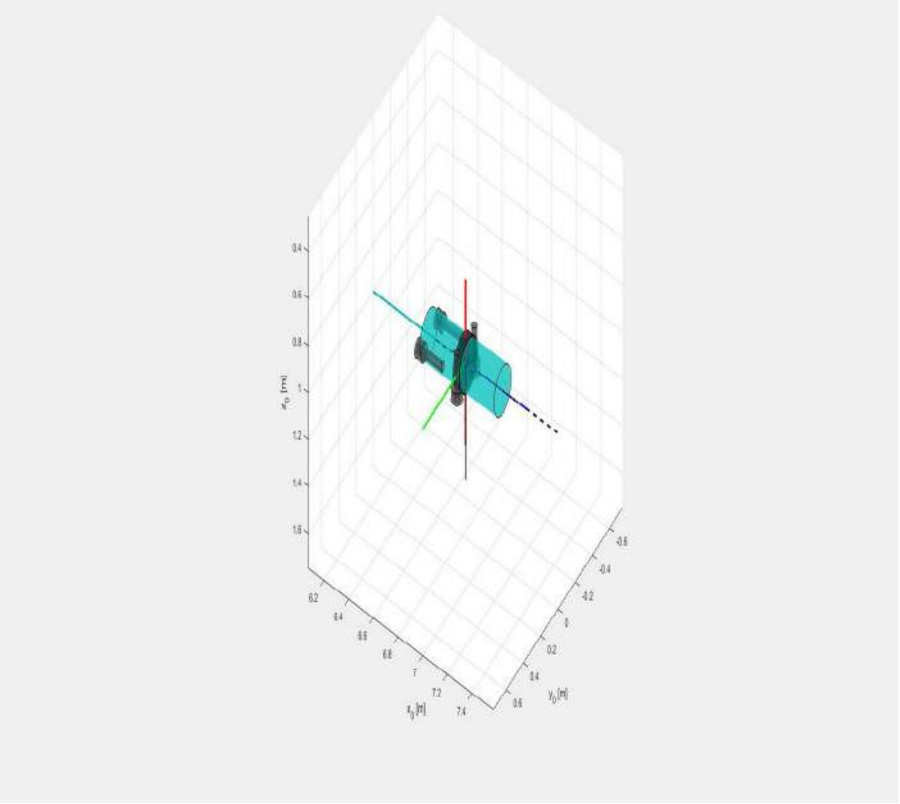
Figure 22: PlaSMAR Configuration 2 - Moment
Actuated DOFs : Surge, Heave, Roll, Pitch, Yaw

Application 1: Seabed Scanning with heading constraint – PlaSMAR Force configuration

RSM -$\mathcal{H}_p$



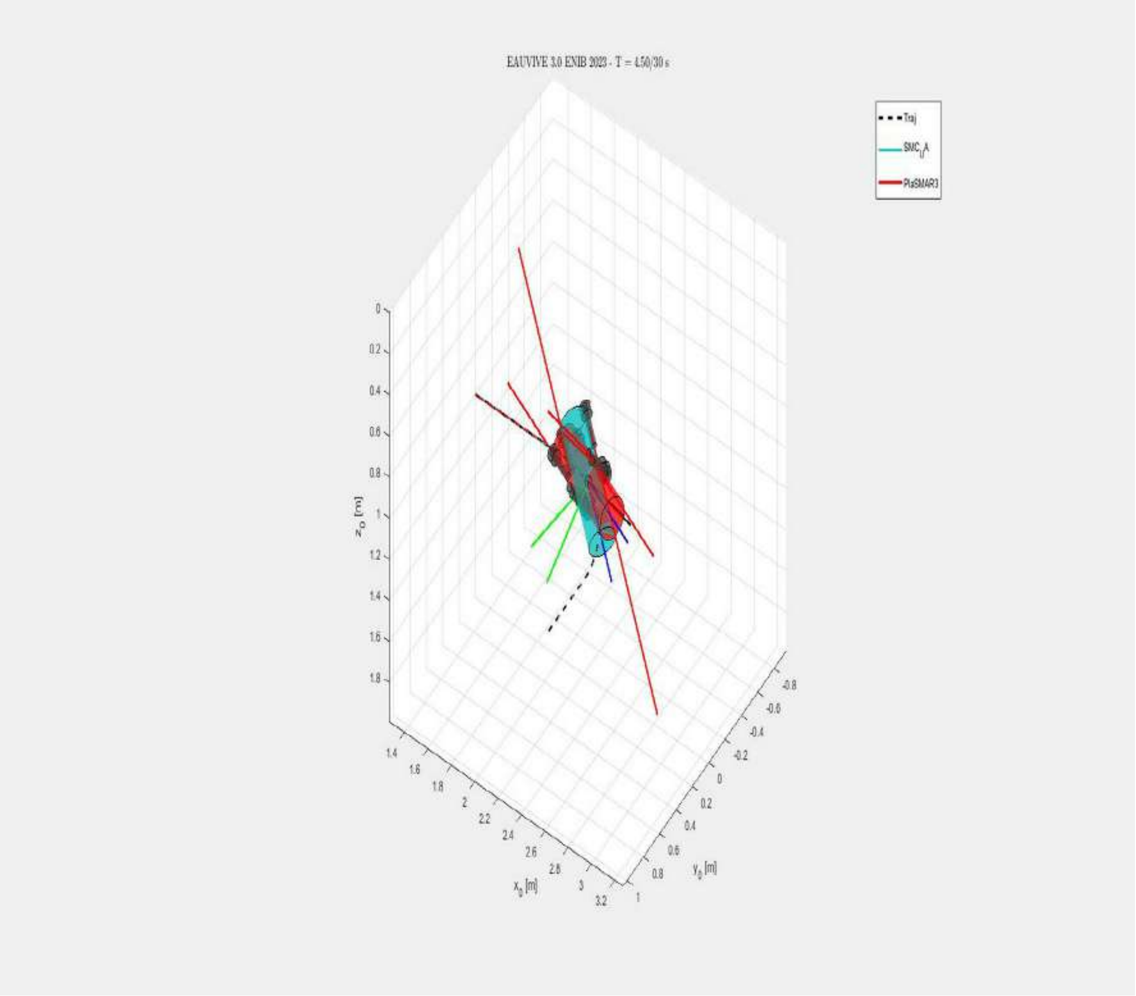
PlaSMAR – Force configuration



Video 5: PlaSMAR in reconfigurable force configuration compared with RSM-$\mathcal{H}_p$ on the seabed scanning task with 0° heading angle constraint

PlaSMAR

Application 2: Seabed Scanning with roll constraint – PlaSMAR Moment configuration



Video 5: PlaSMAR in reconfigurable moment configuration compared with RSM on the seabed scanning task with 45° roll angle constraint

27th November 2023

Thesis Defense

Analysis and Control of Autonomous Underwater Vehicles with Reconfigurable vectoring thrust

Thank you for your attention

Appendix 1: Hovercraft, Brunovský representation

$$\xi_{1,1} = x$$
$$\xi_{1,2} = \dot{x}$$
$$\xi_{2,1} = y$$
$$\xi_{2,2} = \dot{y}$$

$$\dot{\xi}_{1,1} = \xi_{1,2}$$
$$\dot{\xi}_{1,2} = v_1 + \beta\xi_{1,2}$$
$$\dot{\xi}_{2,1} = \xi_{2,2}$$
$$\dot{\xi}_{2,2} = v_2 + \beta\xi_{2,2}$$

$$v_1 = \tau_u \cos\psi$$
$$v_2 = \tau_u \sin\psi$$

Equivalent state candidate for standard representation of the generalized hovercraft subsystem

$$\zeta_1 = x$$
$$\zeta_2 = y$$
$$\zeta_3 = \frac{1}{2}(u^2 + v^2)$$
$$\zeta_4 = \psi + \mathrm{atan}\left(\frac{v}{u}\right)$$