Orthogonal control of Torpedo-like AUV in constrained environment

Quentin Brateau

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ENSTA Bretagne

Context

Introduction

Research laboratory

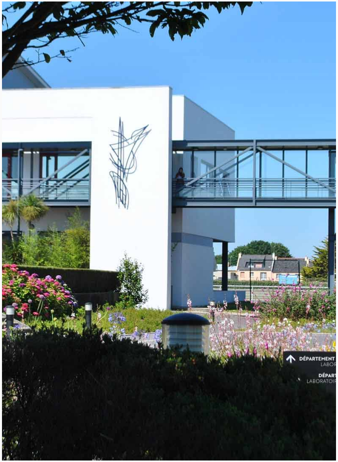
- ENSTA Bretagne, UMR 6285, Lab-STICC

Supervisiors

- Luc Jaulin
- Fabrice Lebars

Funding

- AID funding: Jean-Daniel Masson



AUV

- Control of torpedo-like AUV
- Riptide's micro-uuv

Environment

- Constrained environment
- Pool, harbor, ...

Goals

- Reactivity
- Manoeuvrability

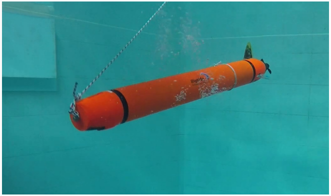


Figure 1: Harbor and Riptide in the ENSTA Bretagne pool

Motivation

Wall avoidance

- Sense wall
- Determine normal vector $\mathbf{u}$
- Reorient AUV orthogonal to $\mathbf{u}$

Control law

- Without singularities
- Based on reliable sensors
- Independant of orientation
- As fast as possible

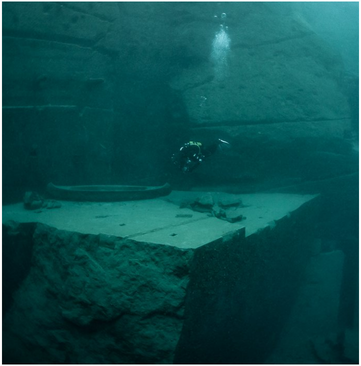


Figure 2: Vodelée quarry - Belgium

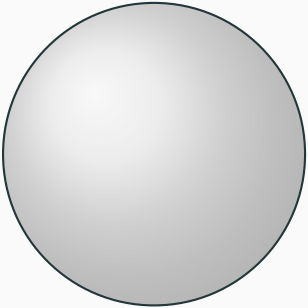


Figure 3: Representation in S^2

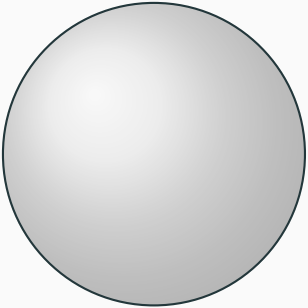
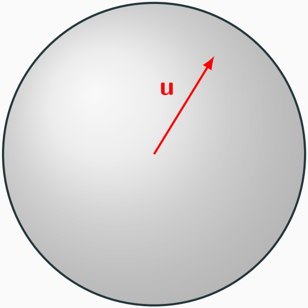


Figure 4: Representation in $SO(3)$

Classical control



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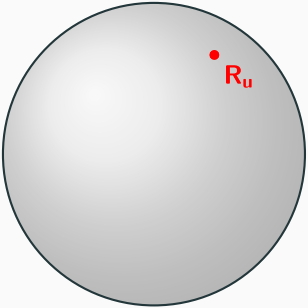

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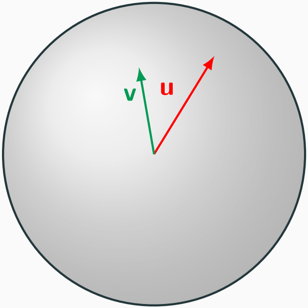

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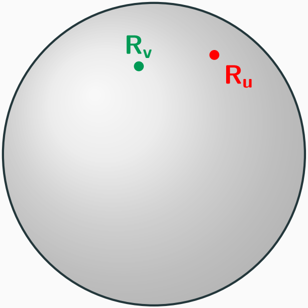

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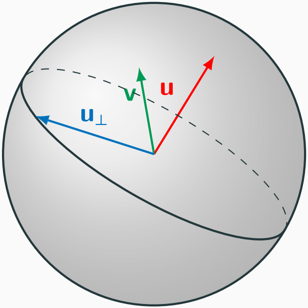

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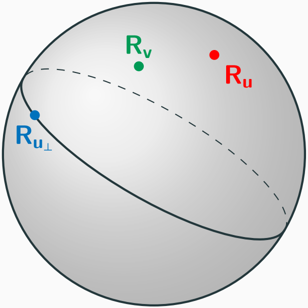

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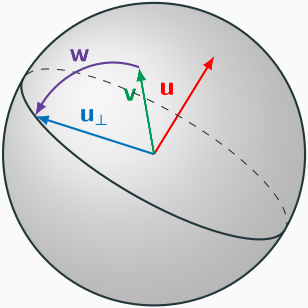

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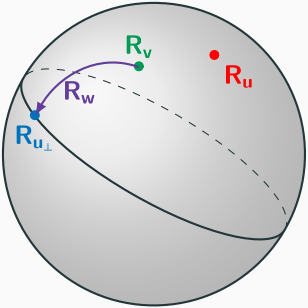

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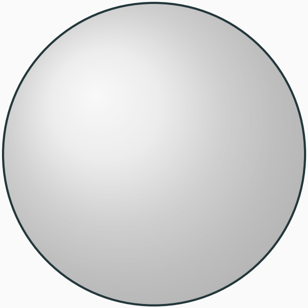
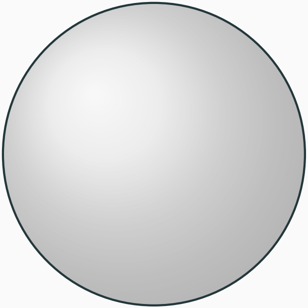


Figure 5: Representation in S^2



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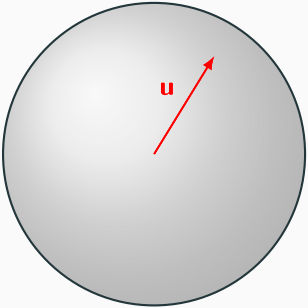
Orthogonal control



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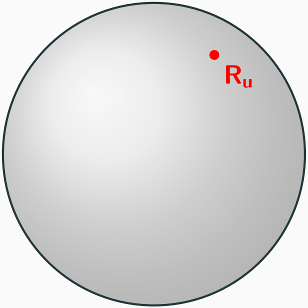

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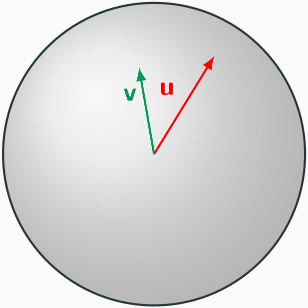

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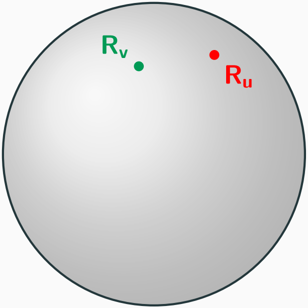

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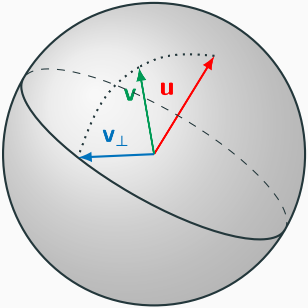

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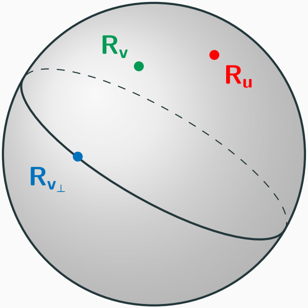

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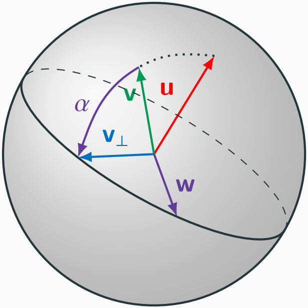

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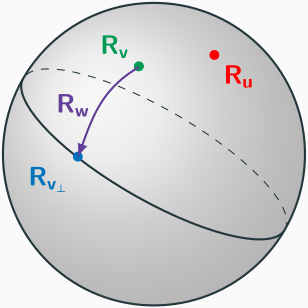


Figure 6: Representation in $SO(3)$

Classical control[1]

Strengths

- Already implemented
- Fully controlled orientation

Weaknesses

- Complete knowledge of **R**
- Set all angles
- Slower reorientation

Orthogonal control

Strengths

- Partial knowledge of **R**
- Set only necessary angles
- Quickest reorientation
- Other angles controllable

Weaknesses

- Uncontrolled direction

[1] Jaulin (2019)

Orthogonal control

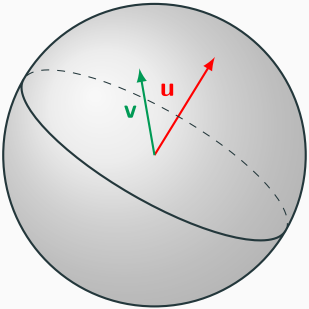
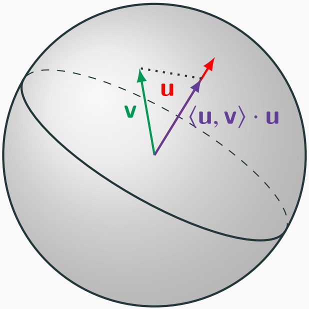


Figure 7: Representation in S^2

Determine $\mathbf{v}_\perp$

$$\mathbf{v}_\perp = \frac{\mathbf{v} - \langle \mathbf{u}, \mathbf{v} \rangle \cdot \mathbf{u}}{\|\mathbf{v} - \langle \mathbf{u}, \mathbf{v} \rangle \cdot \mathbf{u}\|} \tag{1}$$



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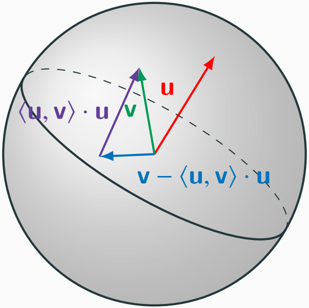

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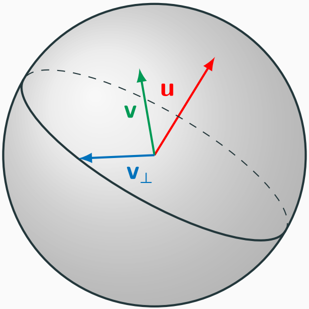

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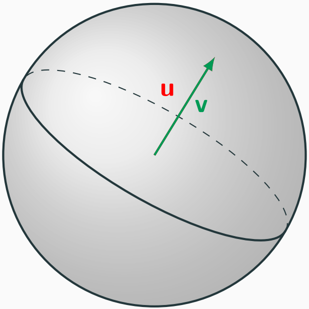

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Determine $\mathbf{v}_\perp$

$$\mathbf{v}_\perp = \frac{\mathbf{v} - \langle \mathbf{u}, \mathbf{v} \rangle \cdot \mathbf{u}}{\|\mathbf{v} - \langle \mathbf{u}, \mathbf{v} \rangle \cdot \mathbf{u}\|} \quad (1)$$

Limitation

Physical singularity when $\mathbf{u} = \mathbf{v}$, as $\mathbf{v}_\perp$ is undefined

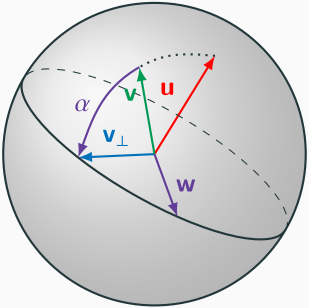
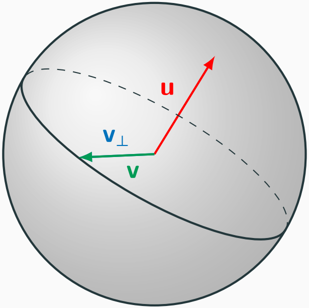


Figure 8: Representation in S^2

Determine ω

$$\mathbf{w} = \mathbf{v} \wedge \mathbf{v}_\perp$$
$$\omega = \frac{arcsin(||\mathbf{w}||)}{||\mathbf{w}||} \cdot \mathbf{w} \tag{2}$$



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Determine ω

$$\begin{aligned} \mathbf{w} &= \mathbf{v} \wedge \mathbf{v}_\perp \\ \omega &= \frac{arcsin(\|\mathbf{w}\|)}{\|\mathbf{w}\|} \cdot \mathbf{w} \end{aligned} \tag{2}$$

Issue

- If $\mathbf{v} = \mathbf{v}_\perp$, $\|\mathbf{w}\| = 0$

Determine ω - Codesido flavor

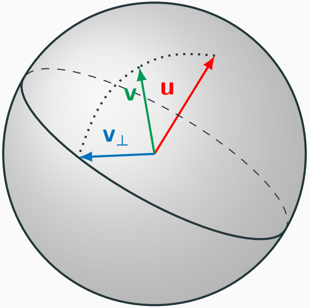
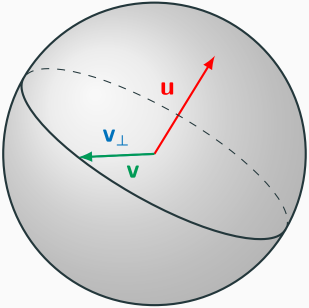


Figure 9: Representation in S^2

Codesido formula[2]

$$\begin{aligned}
\mathbf{K}_{\mathbf{v}}^{\mathbf{v}_\perp} &= \mathbf{v}_\perp \mathbf{v}^T - \mathbf{v}\mathbf{v}_\perp{}^T \\
\mathbf{R}_{\mathbf{v}}^{\mathbf{v}_\perp} &= \mathbf{I}_3 + \mathbf{K}_{\mathbf{v}}^{\mathbf{v}_\perp} + \frac{1}{1+\langle \mathbf{v}, \mathbf{v}_\perp \rangle} (\mathbf{K}_{\mathbf{v}}^{\mathbf{v}_\perp})^2
\end{aligned} \tag{3}$$

[2] Cid and Tojo (2018)



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No singularities

- If $\mathbf{v} = \mathbf{v}_\perp$, $\mathbf{K}_{\mathbf{v}}^{\mathbf{v}_\perp} = \mathbf{O}_3$ and $\mathbf{R}_{\mathbf{v}}^{\mathbf{v}_\perp} = \mathbf{I}_3$

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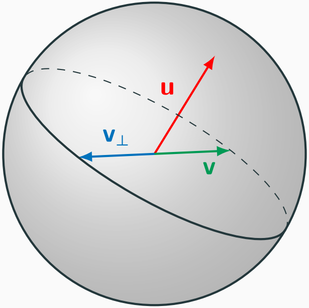

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No singularities

- If $\mathbf{v} = \mathbf{v}_\perp$, $\mathbf{K}_{\mathbf{v}}^{\mathbf{v}_\perp} = \mathbf{O}_3$ and $\mathbf{R}_{\mathbf{v}}^{\mathbf{v}_\perp} = \mathbf{I}_3$
- Singularity when $\langle \mathbf{v}, \mathbf{v}_\perp \rangle = -1$

[2] Cid and Tojo (2018)

2D Examples

Figure 10: Wall avoidance - Classical control

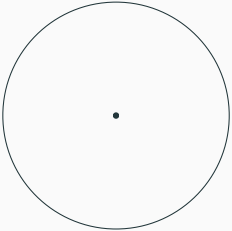
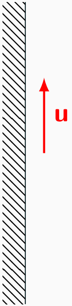


Figure 11: Representation in S^1



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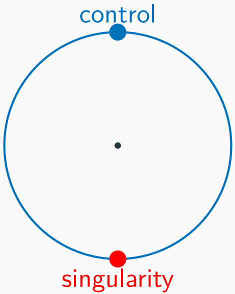

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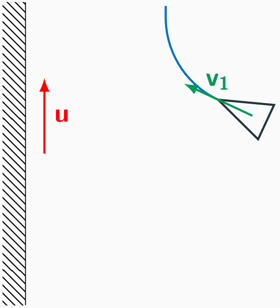

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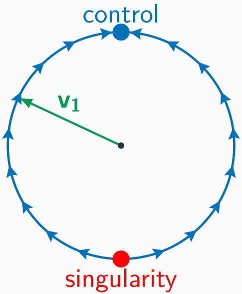

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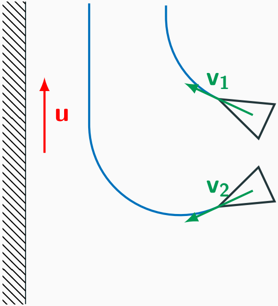

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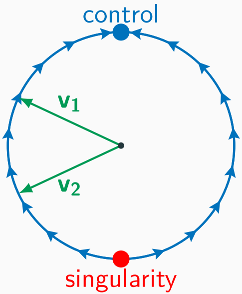

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2D Wall avoidance - Orthogonal control

Figure 12: Wall avoidance - Proposed approach

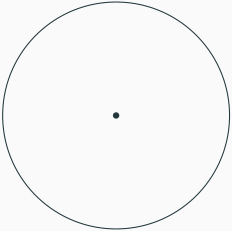
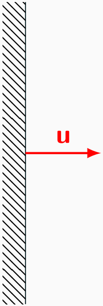


Figure 13: Representation in S^1



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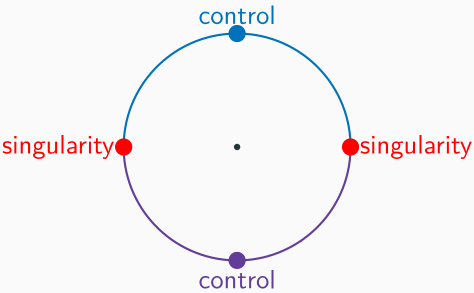

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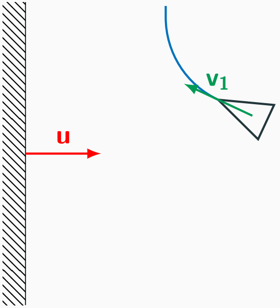

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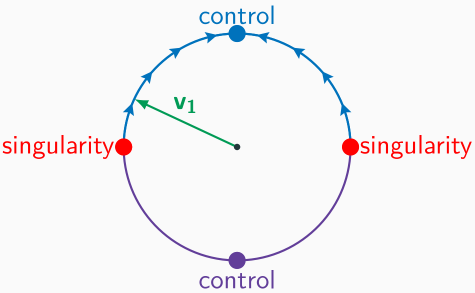

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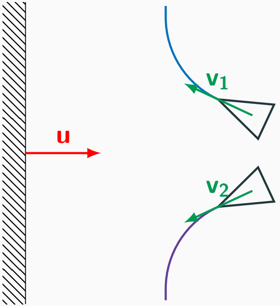

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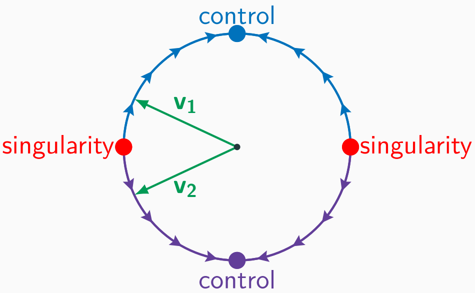


Figure 13: Representation in S^1

2D Pipe following - Classical control

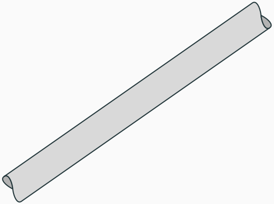


Figure 14: Pipe following - Classical control

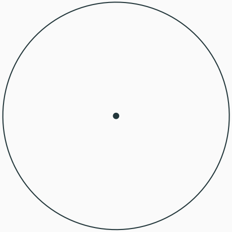
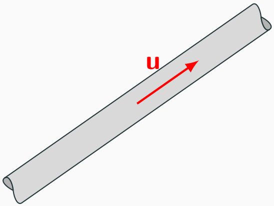


Figure 15: Representation in S^1

2D Pipe following - Classical control



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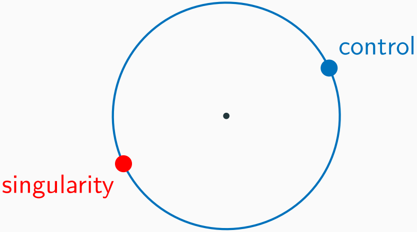

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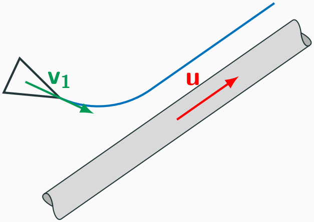

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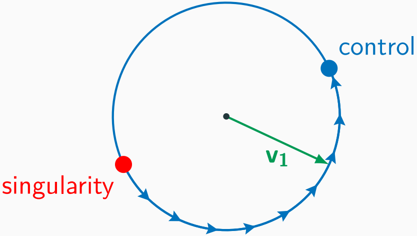

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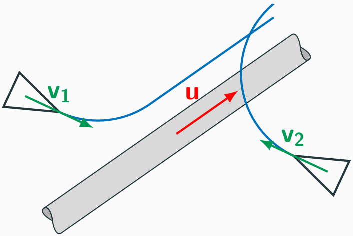

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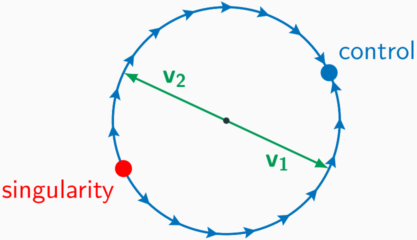

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2D Pipe following - Orthogonal control

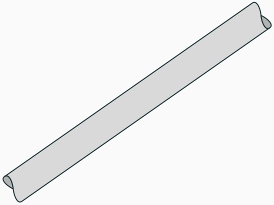


Figure 16: Pipe following - Orthogonal control

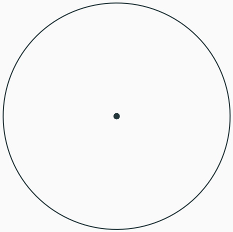


Figure 17: Representation in S^1

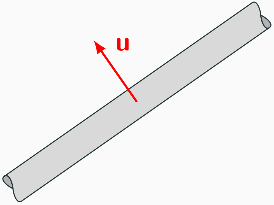


Figure 16: Pipe following - Orthogonal control

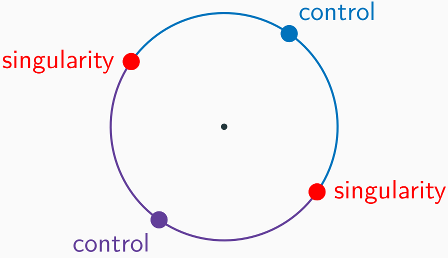


Figure 17: Representation in S^1

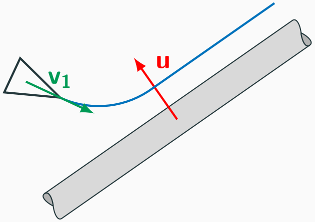


Figure 16: Pipe following - Orthogonal control

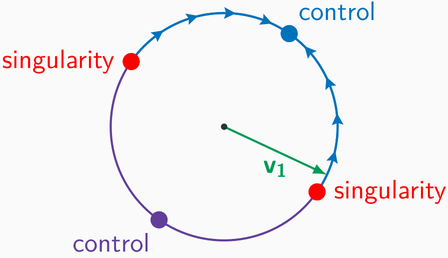


Figure 17: Representation in S^1

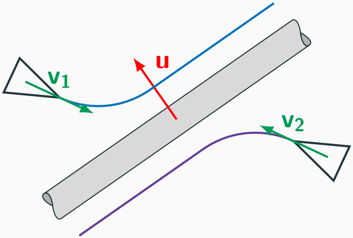


Figure 16: Pipe following - Orthogonal control

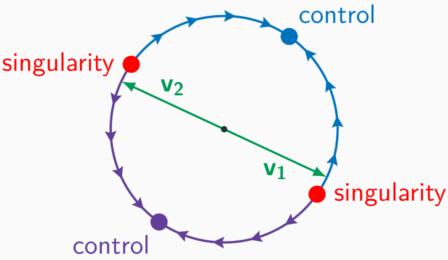


Figure 17: Representation in S^1

AUV application

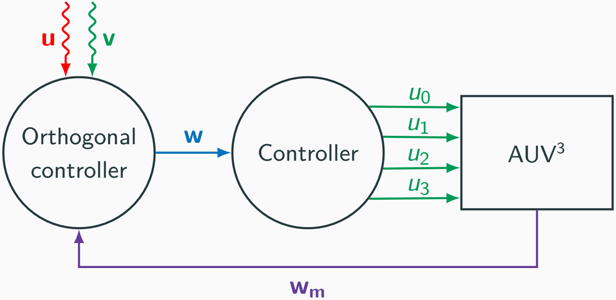


Figure 18: Block diagram - Orthogonal controller

[3] Fossen (2011)

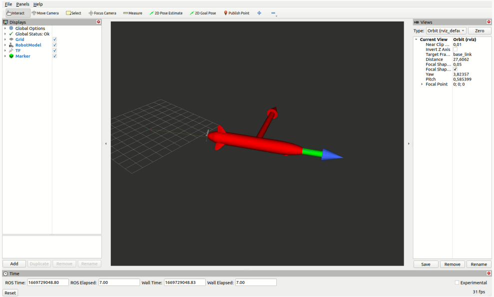


Figure 19: 1 orthogonal constraint

Simulation

- 1 constraint $\mathbf{v} \perp \mathbf{u}$
- $\mathbf{u} = AxisRot(\frac{\pi}{8}, \mathbf{z})$
- $\mathbf{v} = (1, 0, 0)^T$

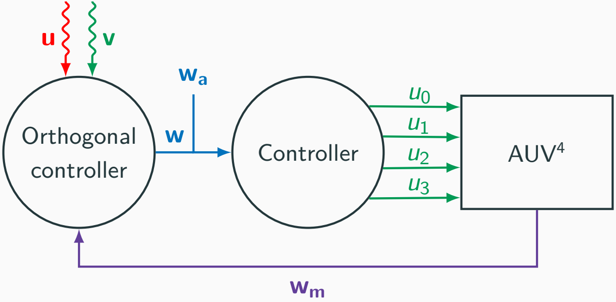


Figure 20: Block diagram - Orthogonal controller

[4]Fossen (2011)

1 Constraint - $\mathbf{w_a}$ injection

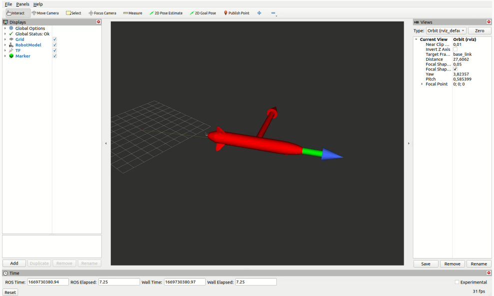


Figure 21: Random orthogonal constraint with $\mathbf{w_a}$ injection

Simulation

- 1 constraint $\mathbf{v} \perp \mathbf{u}$
- $\mathbf{u} = \textit{random}$
- $\mathbf{v} = (1, 0, 0)^T$

$\mathbf{w_a}$ injection

- $\mathbf{w_a} = (w_x, 0, 0)$
- w_x changing every 2 seconds

Flat navigation - $\mathbf{w_a}$ injection

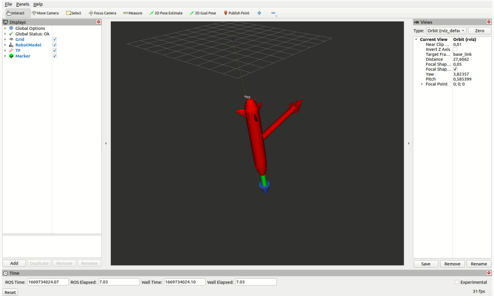


Figure 22: Flat navigation with $\mathbf{w_a}$ injection

Simulation

- 1 constraint $\mathbf{v} \perp \mathbf{u}$
- $\mathbf{u} = (0, 0, 1)^T_w$
- $\mathbf{v} = (1, 0, 0)^T$

$\mathbf{w_a}$ injection

- $w = (w_x, 0, 0)$

Composed orthogonal constraints

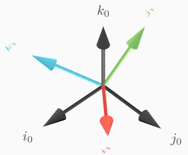


Figure 23: 1 Orthogonal constraint

0 orthogonal constraint

- 0 constraint
- 3 degrees of freedom

Application

- Free navigation

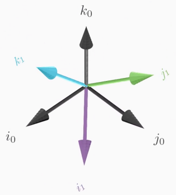


Figure 24: 1 Orthogonal constraint

1 orthogonal constraint

- 1 constraint
- 2 degrees of freedom

Application

- Plane navigation
- Wall avoidance
- Pipe / Rope following

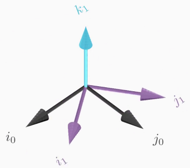


Figure 25: 1 Orthogonal constraint

2 orthogonal constraint

- 2 constraints
- 1 degree of freedom

Application

- Plane navigation with Yaw / Roll control

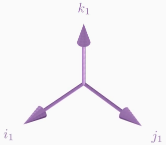


Figure 26: 1 Orthogonal constraint

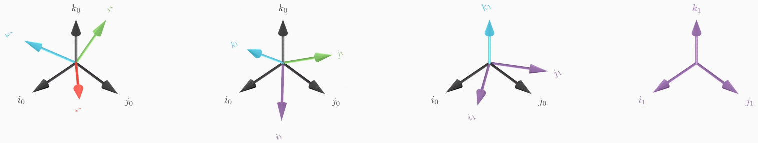
3 orthogonal constraint

- 3 constraints
- 0 degree of freedom

Application

- Align along control basis

Summary of orthogonal constraints



(a) No constraints

(b) 1 constraint $(i_0 \perp k_1)$

(c) 2 constraints $(i_0 \perp k_1)$, $(j_0 \perp k_1)$

(d) 3 constraints $(i_0 \perp k_1)$, $(j_0 \perp k_1)$, $(j_0 \perp i_1)$

Figure 27: All combinations of orthogonal constraints in 3 dimensions

Conclusion

Classical control

- Unsuitable for navigation in constrained environment
- Need a complete knowledge of **R**
- Not responsive enough

Orthogonal control

- Partial knowledge of **R**
- Quickest reorientation
- Let controllable degrees of freedom

Questions?

References

Cid, J. Ángel and F. Adrián F. Tojo (2018). *A Lipschitz condition along a transversal foliation implies local uniqueness for ODEs*.

Fossen, T.I. (2011). *Handbook of Marine Craft Hydrodynamics and Motion Control*.

Jaulin, L. (2019). *Mobile Robotics*.