Cooperative Path Following with Logic Based Communication

From Theory to Real Experiment

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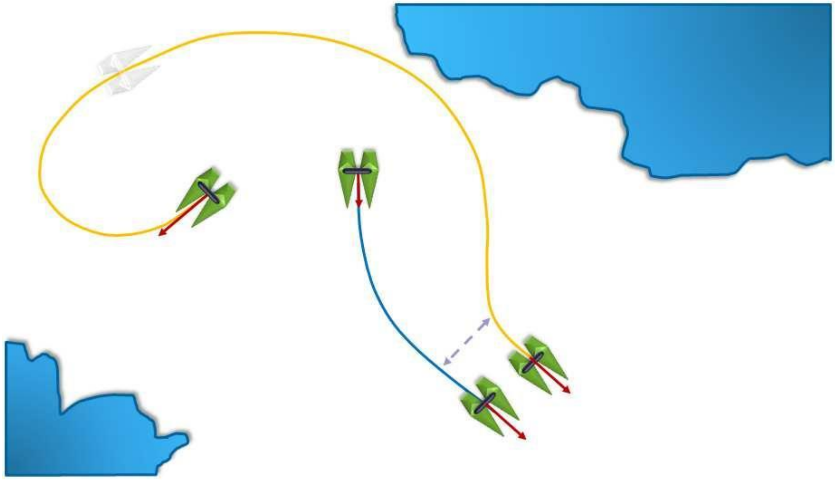
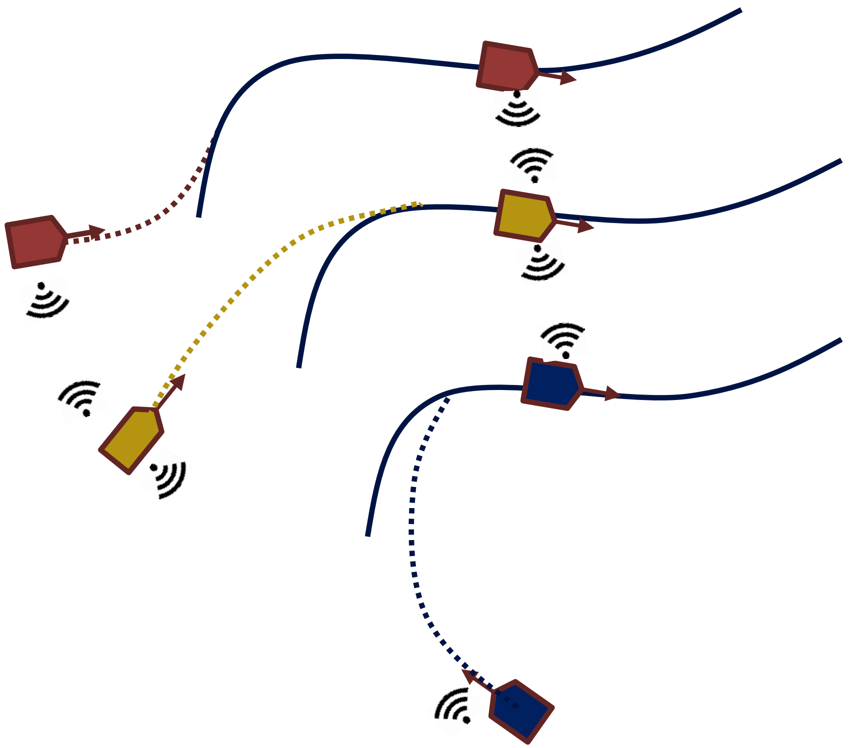
Outline

Outline

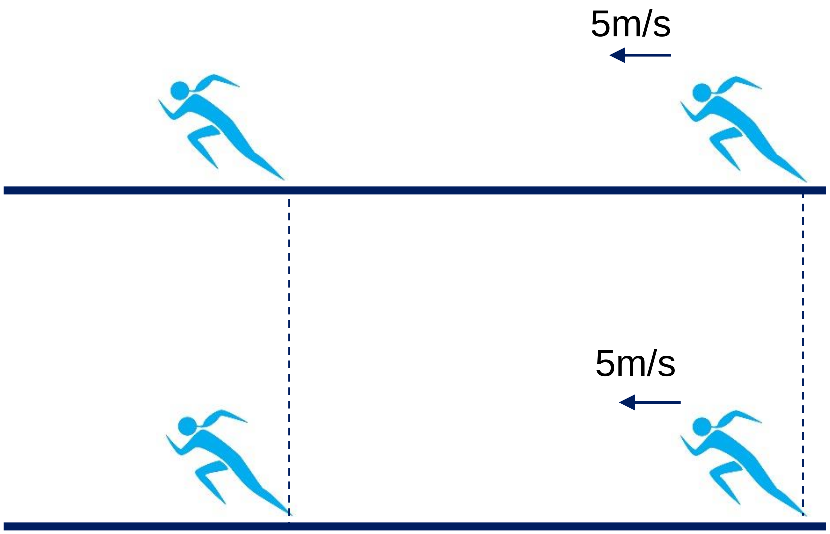


“Go to Formation”

A fleet of vehicles maneuvering to geotechnical acoustic surveys at sea (artist´s rendition - EC WiMUST project)



Fact 1:
To achieve coordination, must have communication among vehicles.



Fact 2:
However, sometimes it is not necessary to communicate. For example, if we start at the same initial position and keep running with the same speed.

Event Triggered communication
(Just talk when it is truly necessary)

Set of $N \geq 2$ N spatial paths

$$\{\mathcal{P}^{[i]} : \gamma^{[i]} \rightarrow [\mathbf{p}_{\mathrm{d}}^{[i]}(\gamma^{[i]}), \psi_{\mathrm{d}}^{[i]}(\gamma^{[i]})]^{\mathrm{T}} \in \mathbb{R}^3, i \in \mathcal{N}\}$$

$\mathcal{N} := \{1, ..., N\}$ denotes the set of the the paths, $\gamma^{[i]}$ denotes the parameterizing variable of path i^{th}.

Set of vehicles

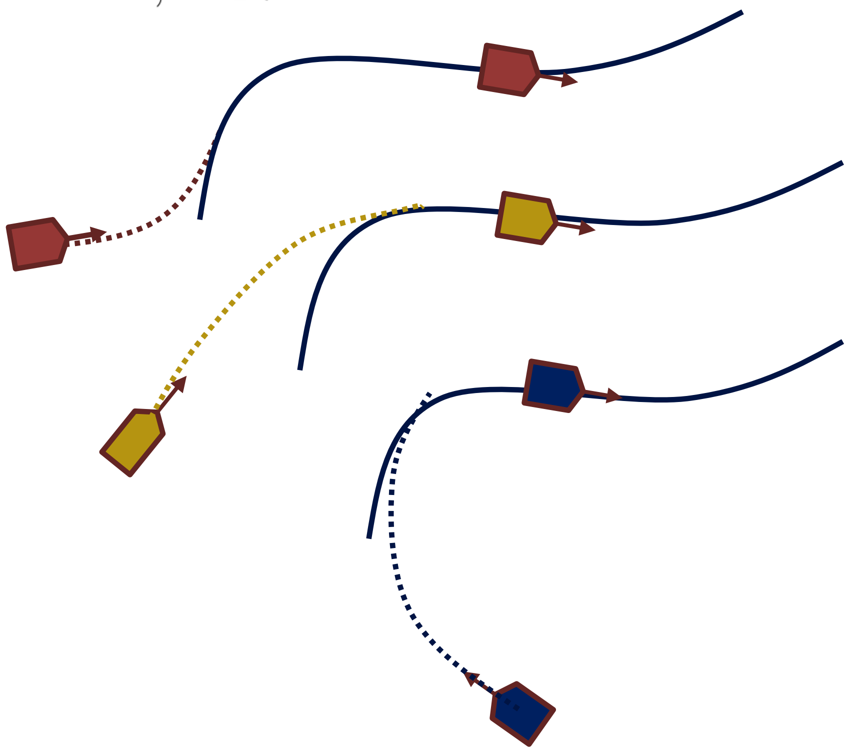
$$\dot{x}^{[i]} = u^{[i]} \cos \psi^{[i]}, \ \dot{y}^{[i]} = u^{[i]} \sin \psi^{[i]}, \ \dot{\psi}^{[i]} = r^{[i]}, \ i \in \mathcal{N}$$

Objectives:

1. All vehicles converge to their assigned paths
2. Path parameters reach consensus, i.e

   $\gamma^{[i]}(t) = \gamma^{[j]}(t) = ... = \gamma^{[N]}(t)$ as $t \rightarrow \infty$
3. Path parameters run with a common desired speed profile

   $\dot{\gamma}^{[1]}(t) = \dot{\gamma}^{[2]}(t) = ... = \dot{\gamma}^{[N]}(t) = v_d$ as $t \rightarrow \infty$



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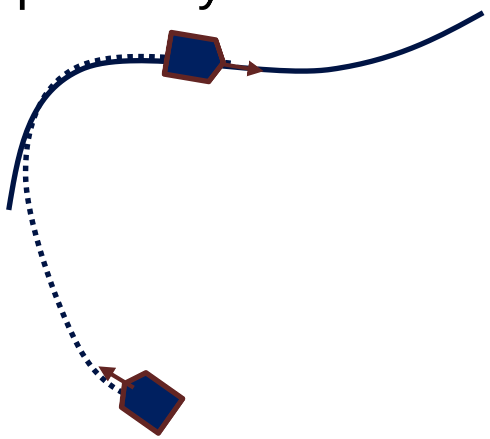
Objectives:

1. Derive the vehicle converge to the path
2. Derive the path parameter such that its speed asymptotically converge to a desired speed profile



Tools

Nonlinear Control

LINE-OF-SIGHT PATH FOLLOWING OF UNDERACTUATED MARINE CRAFT

Thor I. Fossen [*,1] Morten Breivik [*] Roger Skjetne [*]

1362 IEEE TRANSACTIONS ON AUTOMATIC CONTROL, VOL. 52, NO. 8, AUGUST 2007

Trajectory-Tracking and Path-Following of Underactuated Autonomous Vehicles With Parametric Modeling Uncertainty

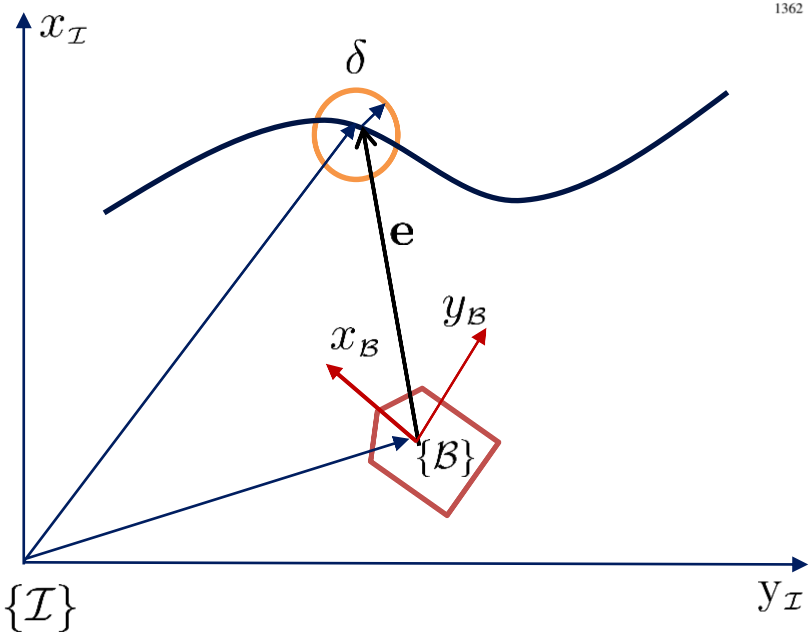
A. Pedro Aguiar, *Member, IEEE*, and João P. Hespanha, *Senior Member, IEEE*

Nonsingular path following control of a unicycle in the presence of parametric modelling uncertainties

L. Lapierre[1,*,†], D. Soetanto[2,‡] and A. Pascoal[2,§]

Trajectory-tracking and Path-following Controllers for Constrained Underactuated Vehicles using Model Predictive Control*

Andrea Alessandretti[1 2], A. Pedro Aguiar[3] and Colin N. Jones[1]



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Trajectory-Tracking and Path-Following of Underactuated Autonomous Vehicles With Parametric Modeling Uncertainty

A. Pedro Aguiar, *Member, IEEE*, and João P. Hespanha, *Senior Member, IEEE*

Idea: Formulate path following error in the body frame of the vehicle.

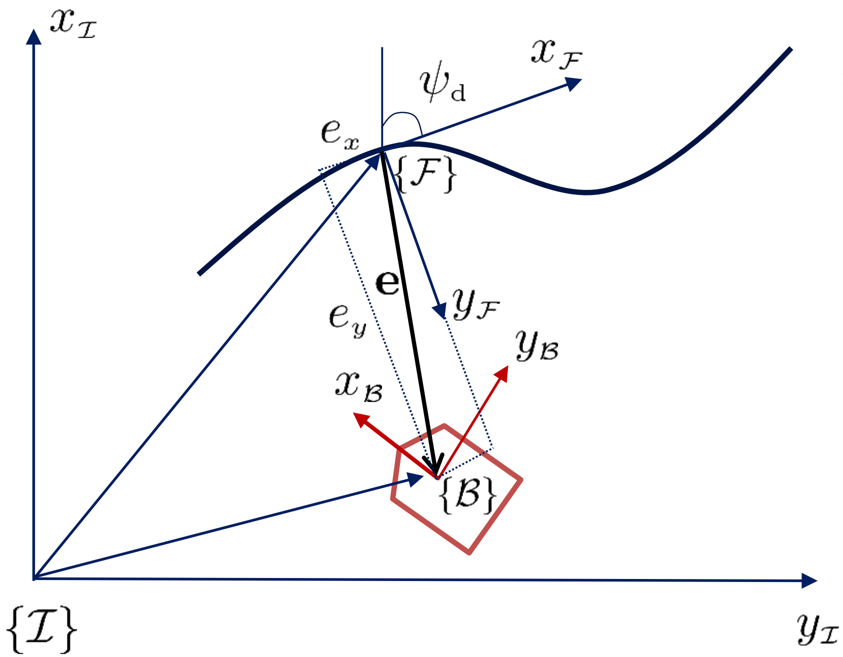
Task: Stabilize the path following error

Path Following Controller- Method 1

$$\mathbf{u}_d = \begin{bmatrix} u \\ r \end{bmatrix} = \Delta^{-1}\left(-K(\mathbf{e}-\boldsymbol{\delta}) + R^{\mathrm{T}}(\psi)\frac{\partial \mathbf{p}_{\mathrm{d}}(\gamma)}{\partial \gamma} v_d\right)$$

where $\boldsymbol{\delta} = [\delta,\ 0]^{\mathrm{T}},\ \delta > 0,\ \Delta = \begin{bmatrix} 1 & 0 \\ 0 & \delta \end{bmatrix},\ K = \begin{bmatrix} k_1 & 0 \\ 0 & k_2 \end{bmatrix}, k_1, k_2 > 0$

Then $\mathbf{e} = \boldsymbol{\delta}$ is GAS.



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Int. J. Robust Nonlinear Control 2006; **16**:485–503
Published online 20 April 2006 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/rnc.1075

Nonsingular path following control of a unicycle in the presence of parametric modelling uncertainties

L. Lapierre[1,*,†], D. Soetanto[2,‡] and A. Pascoal[2,§]

Idea: Formulate path following error in the Frenet-Serret frame.

Task: Stabilize the path following error

Path Following Controller- Method 2

Consider a special case, $\gamma \equiv s$ where s is the arc-lenght of the path. Let $\psi_e = \psi - \psi_d$ be the orientation error. Path following control law

$$u = v_{\mathrm{d}}; \;\; \dot{\gamma} = u\cos(\psi_e) + k_1 e_x$$

$$\dot{\psi}_e = \dot{\delta} - k e_y u \frac{\sin(\psi_e - \sin\delta}{\psi_e - \delta} - k_2(\psi_e - \delta)$$

where k_1, k_2, k are positive. $\delta(u, e_y) = -\theta_a \tanh(k_\delta e_y u)$ is the tuning function. Then $\mathbf{e}$ is GAS.

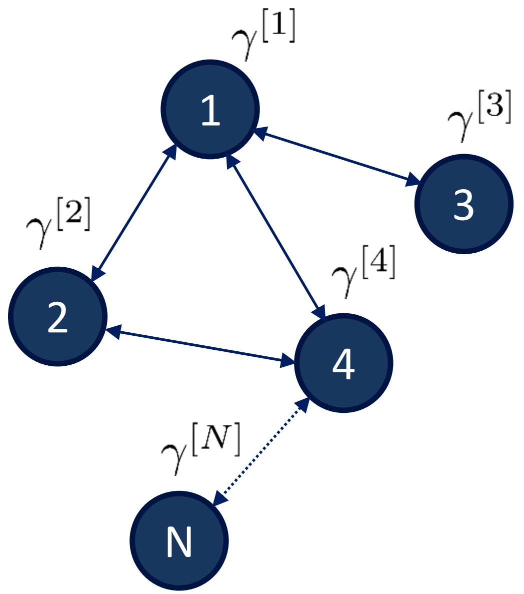
Outline

Objectives:

Given a set of N agents, each agent has dynamics described by

$$\dot{\gamma}^{[i]} = v_d + v_c^{[i]}$$

Derive a distributed control law for $v_c^{[i]}$ *such that all agent reach consensus asymtotically, i.e* $\gamma^{[1]}(t) = \gamma^{[2]}(t) = ... = \gamma^{[N]}(t)$ *as* $t \to \infty$



Tools

Graph theory, Network Control

Consensus Protocols for Networks of Dynamic Agents

Reza Olfati Saber Richard M. Murray
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California Institute of Technology
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e-mail: {olfati,murray}@cds.caltech.edu

On Consensus Algorithms for Double-integrator Dynamics

Wei Ren

Distributed Event-Triggered Control for Multi-Agent Systems

Dimos V. Dimarogonas, Emilio Frazzoli, and Karl H. Johansson

Let $\mathcal{G}(\mathcal{V},\mathcal{E})$ be the graph induced by the internetwork.
$\mathcal{V}$ is the set of vertices and $\mathcal{E}$ is the set of edges.
The laplacian matrix L characterizes the graph

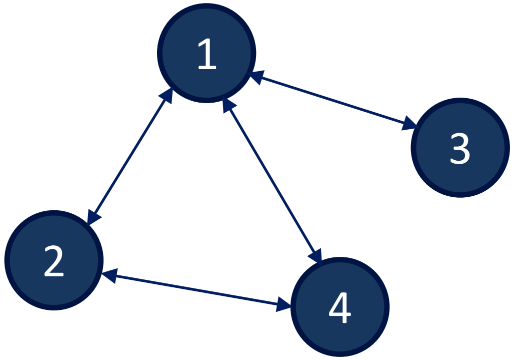
$$L = D - A$$

where D is the degree matrix and
A is the adjacency matrix of the graph.

$$D = \{d_{ij}\} = \begin{cases} |\mathcal{N}_i|, & \text{if } i = j \\ 0, & \text{otherwise} \end{cases}$$

$$A = \{a_{ij}\} = \begin{cases} 1, & \text{if } j \in \mathcal{N}_i \\ 0, & \text{otherwise} \end{cases}$$

$\mathcal{N}_i$: set of neighboring agents of agent i^{th}
$|\mathcal{N}_i|$: is the cardinality of $\mathcal{N}_i$



An example of undirected graph

$$\mathcal{G}(\mathcal{V},\mathcal{E})$$

$$\mathcal{V} = \{1,2,3,4\}$$

$$\mathcal{E} = \{(1,2),(1,3),(1,4),(2,4)\}$$

$$D = \begin{matrix} 3 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 2 \end{matrix} \quad A = \begin{matrix} 0 & 1 & 1 & 1 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \end{matrix} \quad L = \begin{matrix} 3 & -1 & -1 & -1 \\ -1 & 2 & 0 & -1 \\ -1 & 0 & 1 & 0 \\ -1 & -1 & 0 & 2 \end{matrix}$$

Fact-[Properties of Laplacian matrix]
If the graph is undirected and connected

- L is symetric and positive semi definite.
- L has a simple eigenvalue at zero with an associated eigenvector $\mathbf{1}$ and the remaining eigenvalues are all positive.

Result -

Given a set of N agents, each agent has dynamics described by

$$\dot{\gamma}^{[i]} = v_d + v_{\text{c}}^{[i]}$$

The distributed control law for $v_{\text{c}}^{[i]}$ given by

$$v_{\text{c}}^{[i]} = -k\Big(\sum_{j \in \mathcal{N}^{[i]}} \gamma^{[i]} - \gamma^{[j]}\Big) \text{ for all } i \in \mathcal{N}$$

solves the coordination problem, i.e $\gamma^{[1]}(t) = \gamma^{[2]}(t) = \ldots = \gamma^{[N]}(t)$ *as* $t \to \infty$ *where k is the positive gain.*

Estimate states of neighboring agents

Optimal Communication Logics in Networked Control Systems

Yonggang Xu João P. Hespanha
Dept. of Electrical and Computer Eng., Univ. of California, Santa Barbara, CA 93106

With logic based communication, new coordination control law

$$v_{\mathrm{c}}^{[i]} = -k\left(\sum_{j\in\mathcal{N}^{[i]}} \gamma^{[i]} - \hat{\gamma}^{[j]}\right) \text{ for all } i \in \mathcal{N}$$

Bank of estimators for neighboring agents

where

$$\dot{\hat{\gamma}}^{[j]}(t) = v_{\mathrm{d}} \text{ for } t_k \le t \le t_{k+1} \text{ and } \hat{\gamma}^{[j]}(t^{[j]}) = \hat{\gamma}^{[j]}(t_k^{[j]}), j \in \mathcal{N}^{[i]}$$

Internal estimator

$$\dot{\hat{\gamma}}^{[i]}(t) = v_{\mathrm{d}} \text{ for } t_k \le t \le t_{k+1} \text{ and } \hat{\gamma}^{[i]}(t^{[i]}) = \hat{\gamma}^{[i]}(t_k^{[i]})$$

Event triggered communication condition:
Let $|\tilde{\gamma}^{[i]}| = \gamma^{[i]} - \hat{\gamma}^{[i]}$ be the estimation error.

$$|\tilde{\gamma}^{[i]}| > \epsilon, \ \ \epsilon > 0$$

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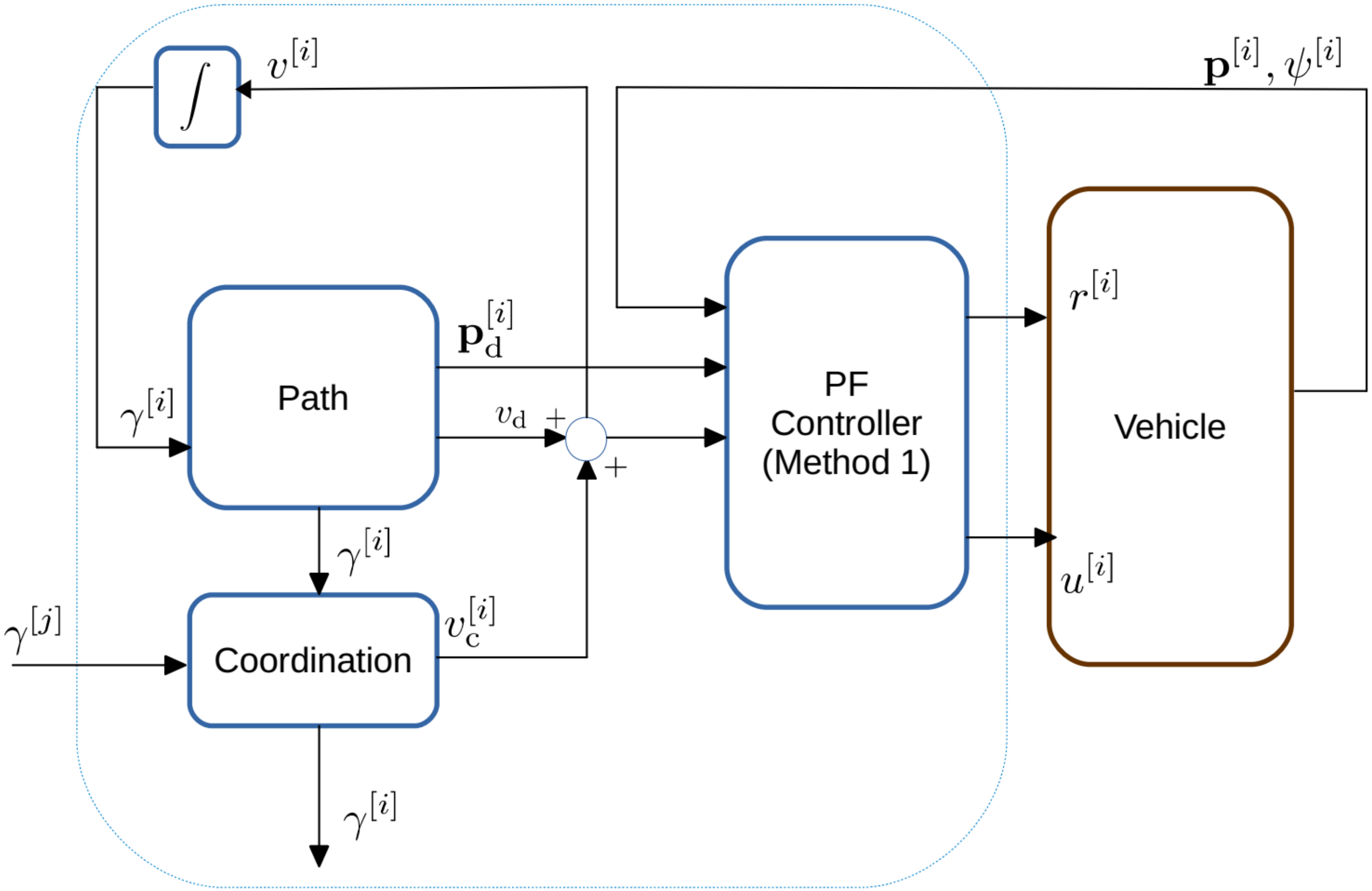
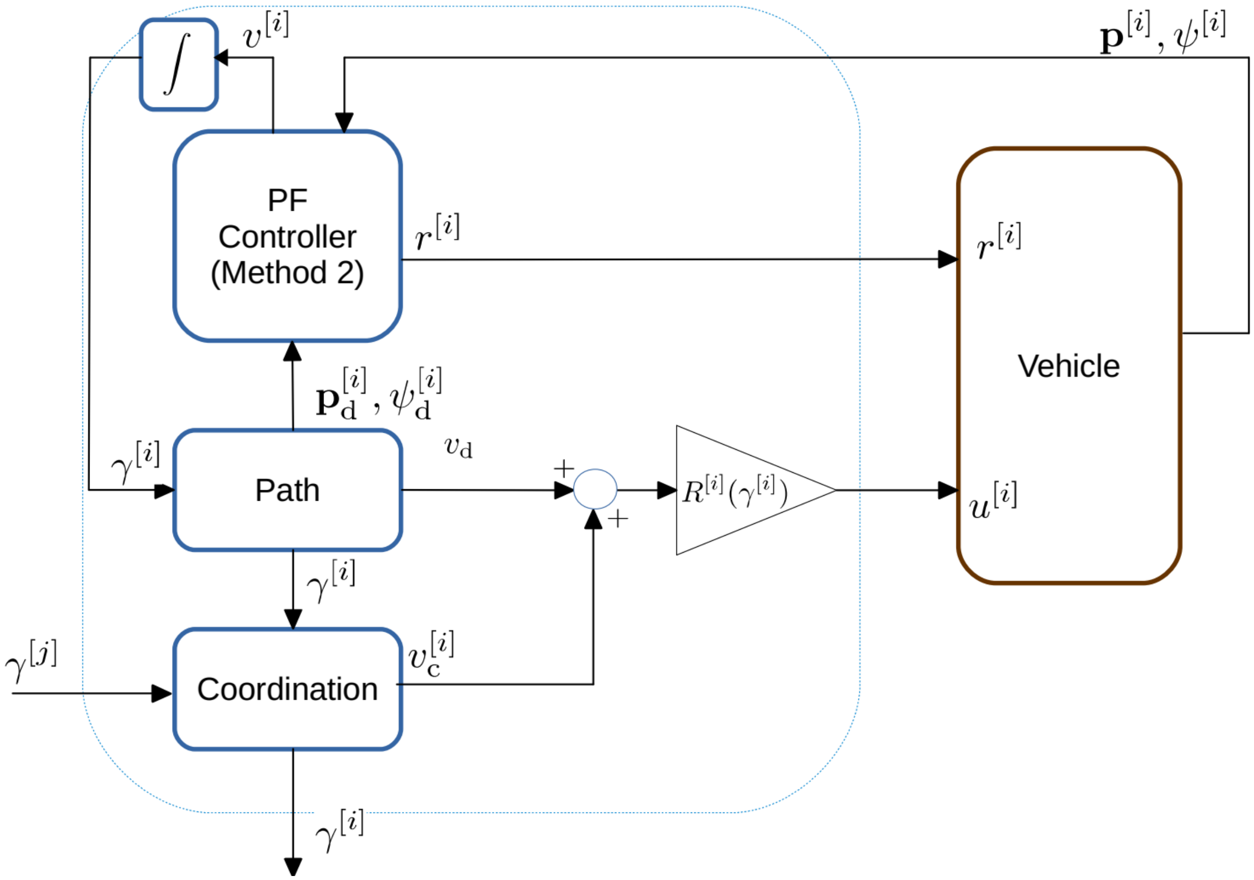


CPF control system with path following controller using method 1

Result 1:

CPF system is ISS respect to the error of estimation of the path parameters, which is bounded by ε , the error of tracking desired heading rate and desired speed of the autopilot.



CPF control system with path following controller using method 2

Result 2:
CPF system is ISS respect to the error of estimation of the path parameters, which is bounded by ε , the error of tracking desired heading rate and desired speed of the autopilot.

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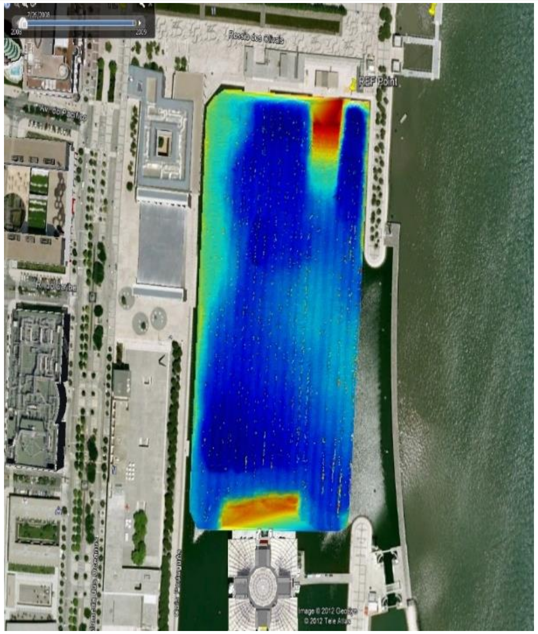
Set-up

- 3 Medusa surface vehicles
- In-line formation
- Speed profile : 0.5m/s
- Lawnmower Mission

Key assumptions

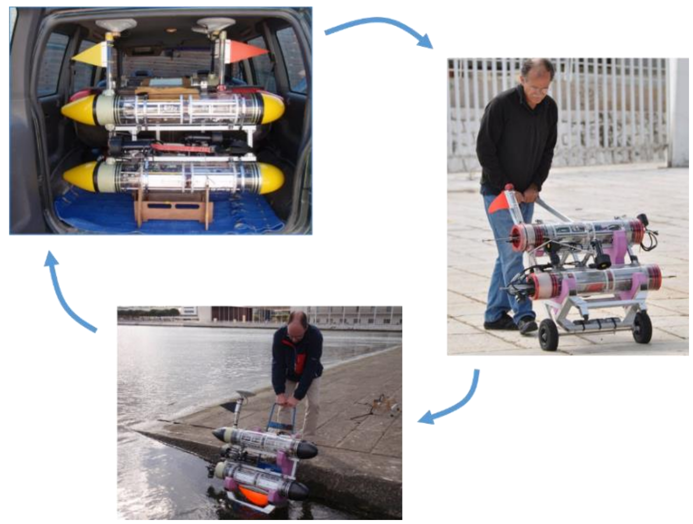
- No delay in communication

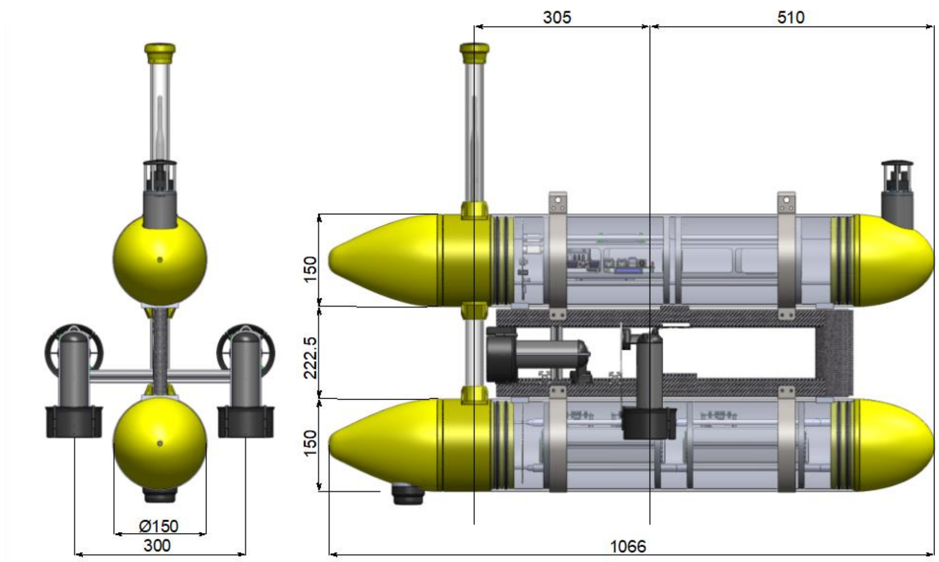


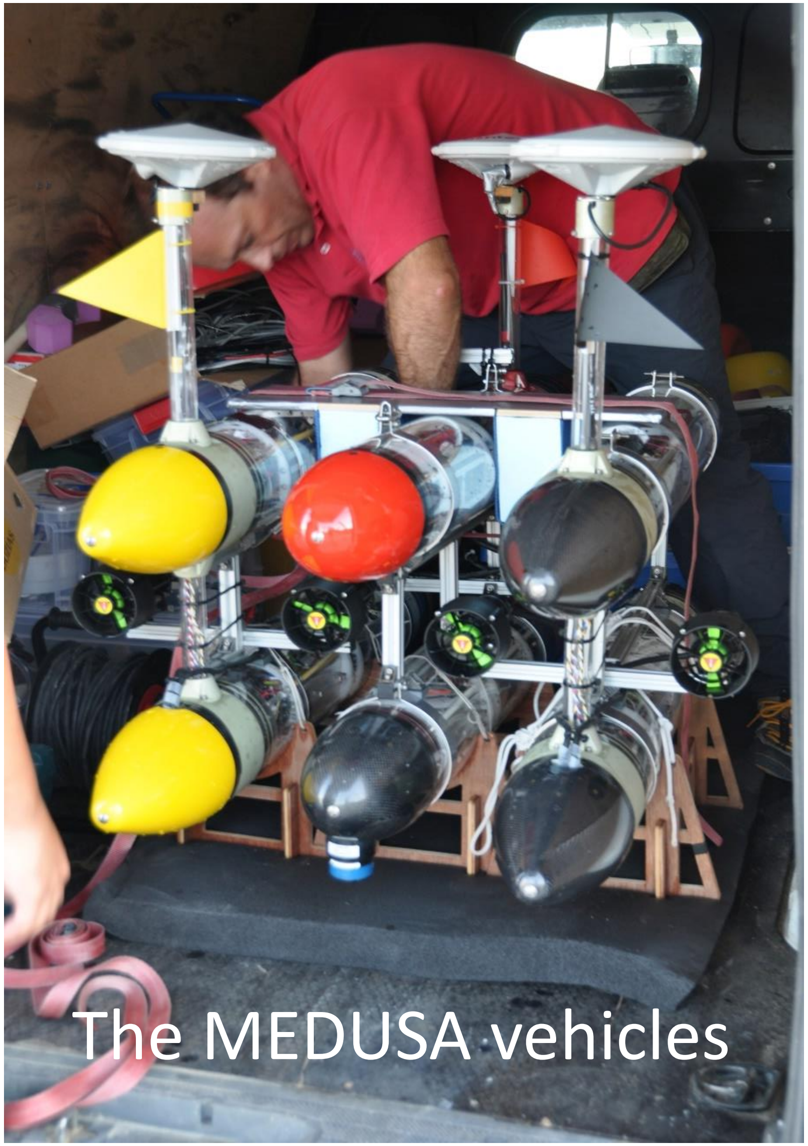
MEDUSA vehicles

EXPO’98 Site, Lisbon, PT

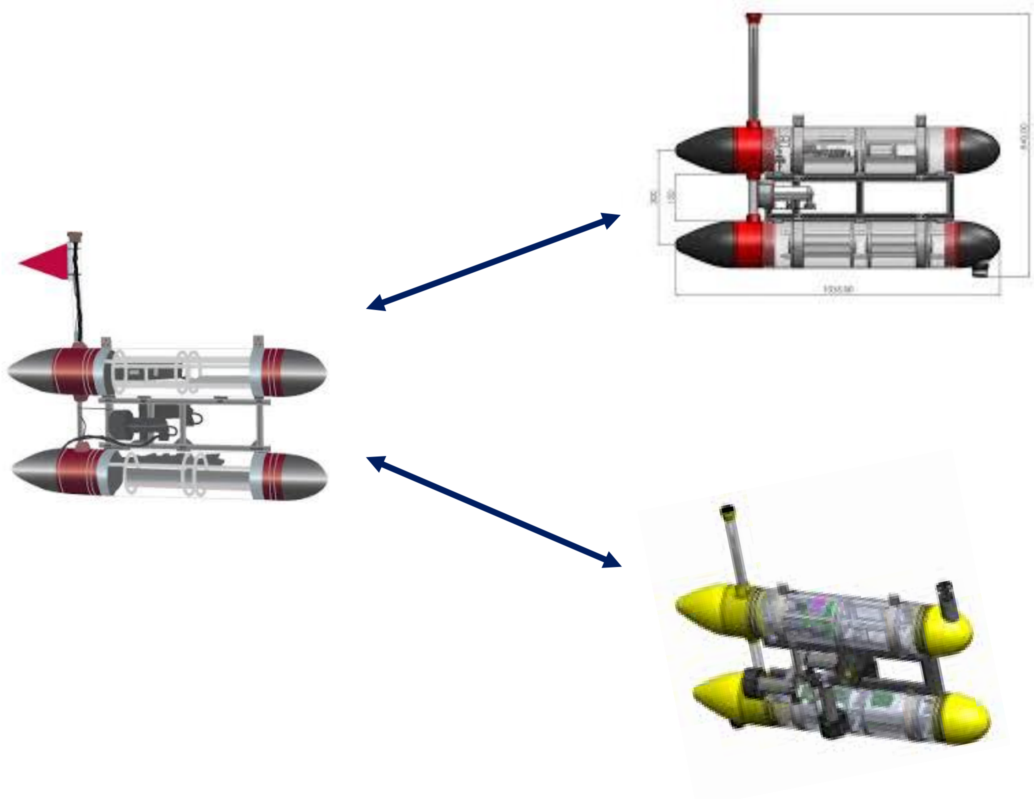
- Surface and diving versions: $MEDUSA_S$ and $MEDUSA_D$
- Two-body shape, 30 kg, easy launch & recovery
- Depths up to 50 m
- Five units built since 2009



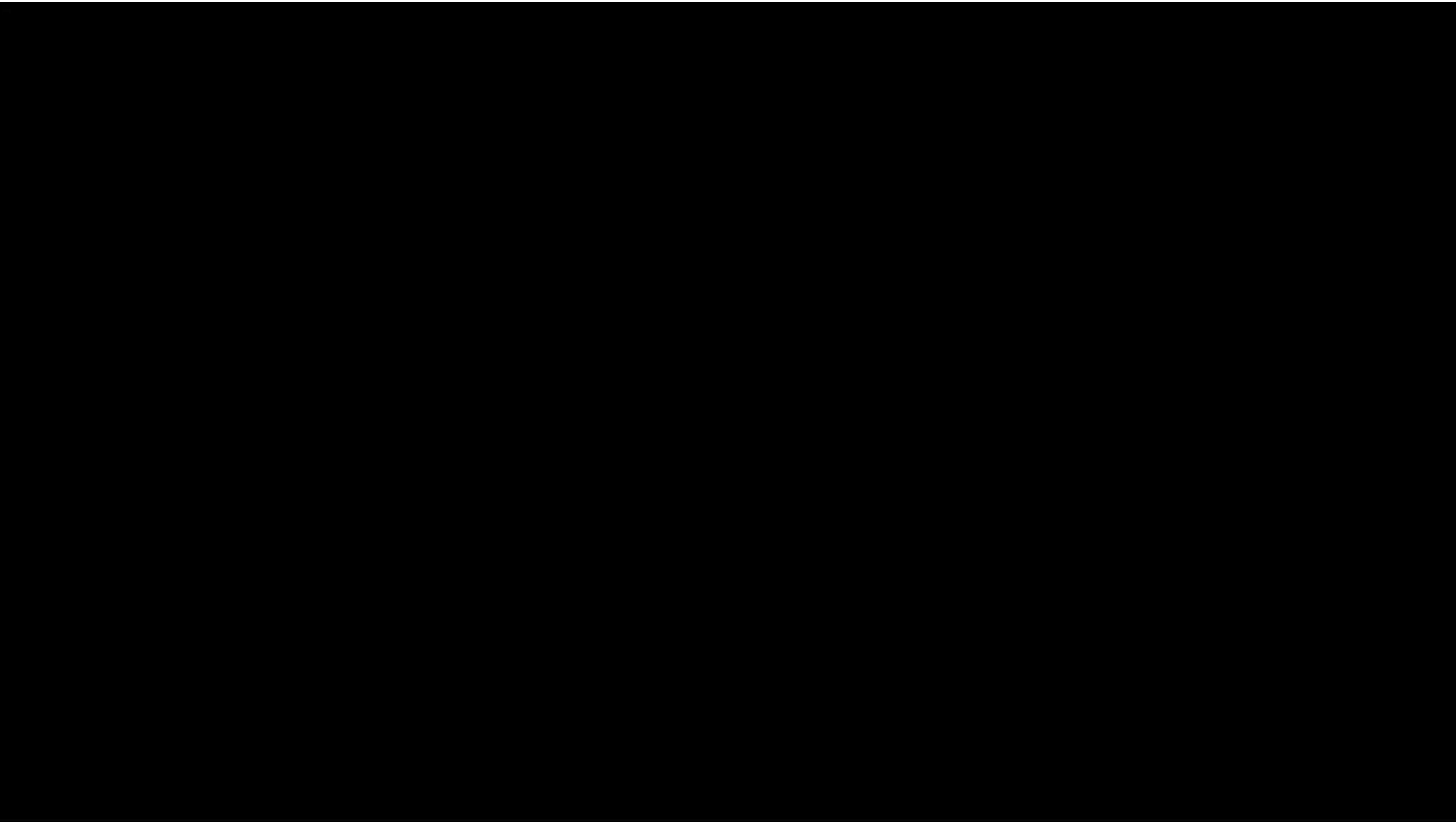



The MEDUSA vehicles

- Network Topology : undirected
- Communication medium: wifi



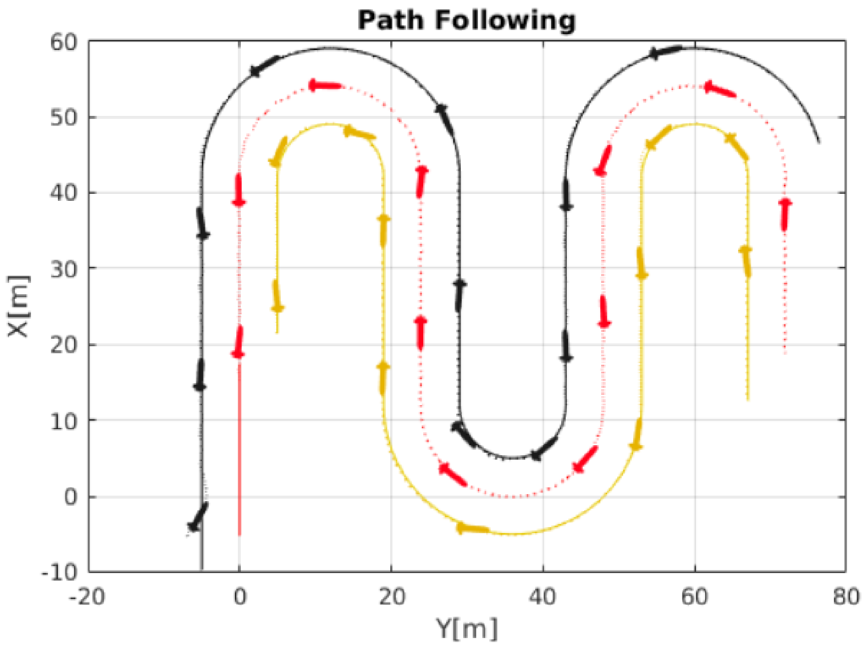
Let’s go to water

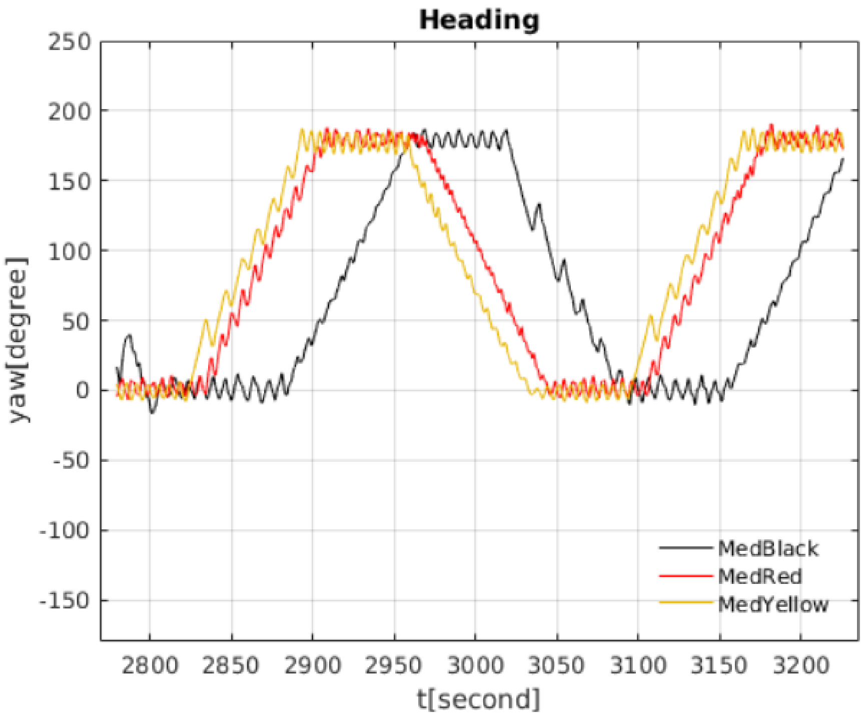


Mission : Lawnmower - Straight-line segments (30m)

- Circumference segments (Radius: 7m, 10m, 12m)

Path following controller : Method 1





Mission : Lawnmower - Straight-line segments (30m)

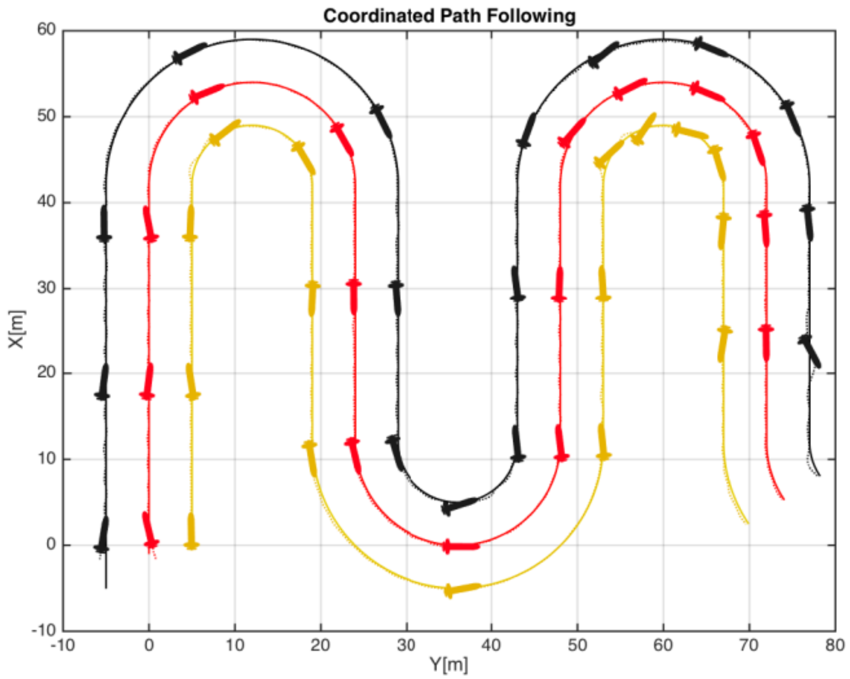
- Circumference segments (Radius: 7m, 10m, 12m)

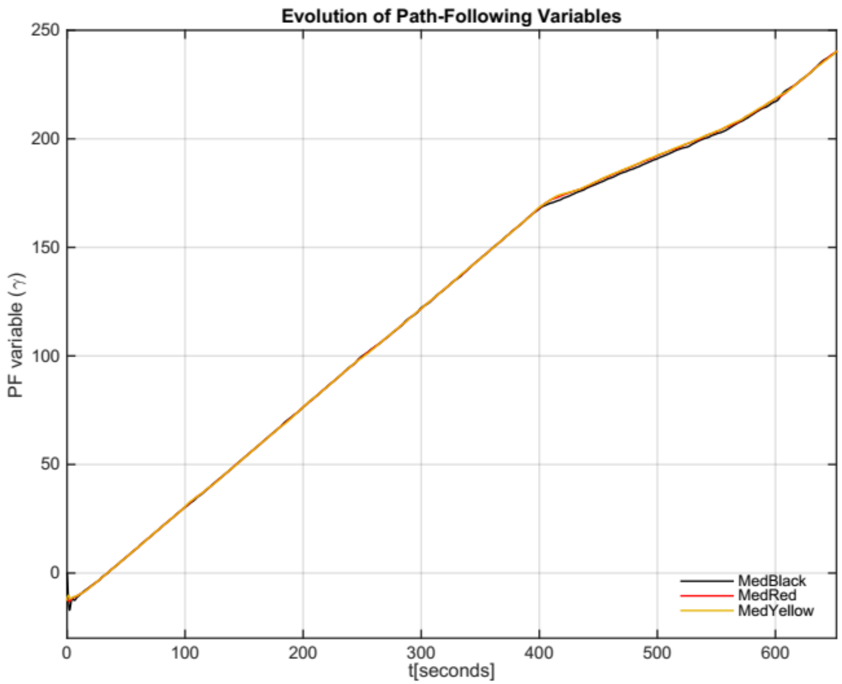
Desired formation : Line formation

Path speed profile : $v_{\mathrm{d}} = 0.5\mathrm{m/s}$

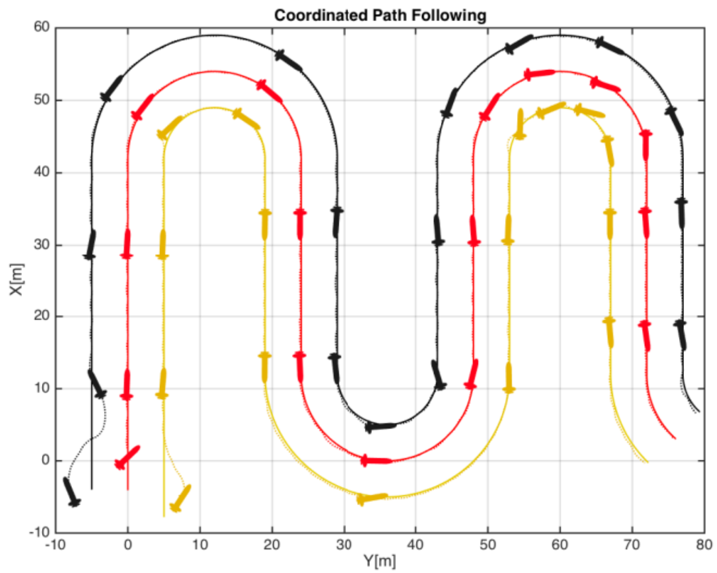
Path following controller : Method 1

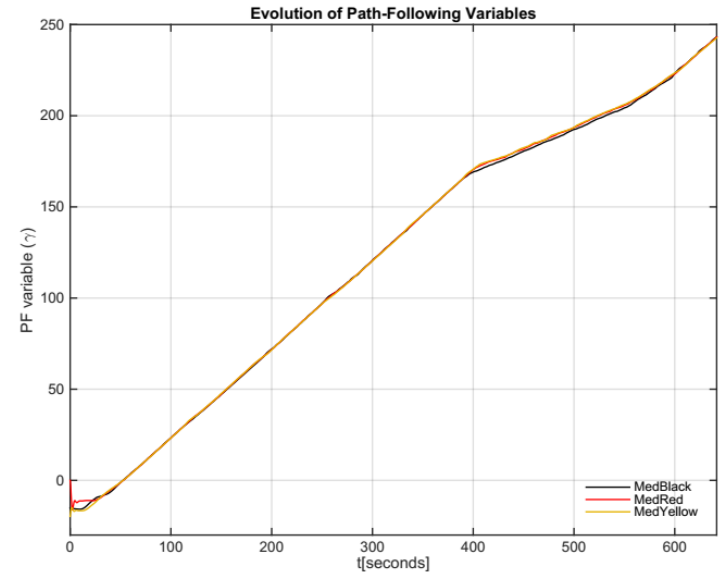
Periodic communication time : 0.2s

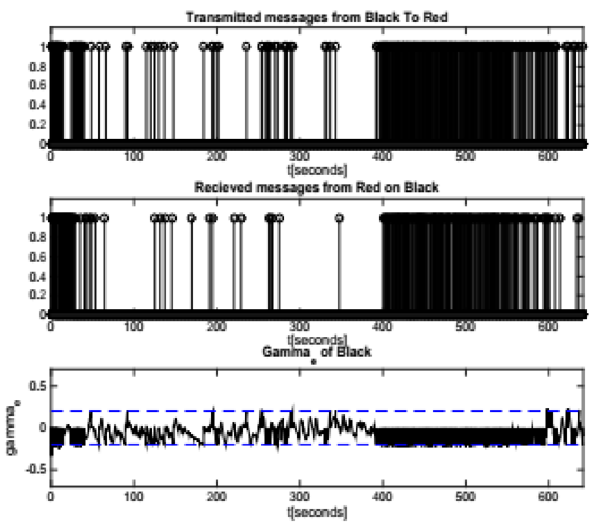




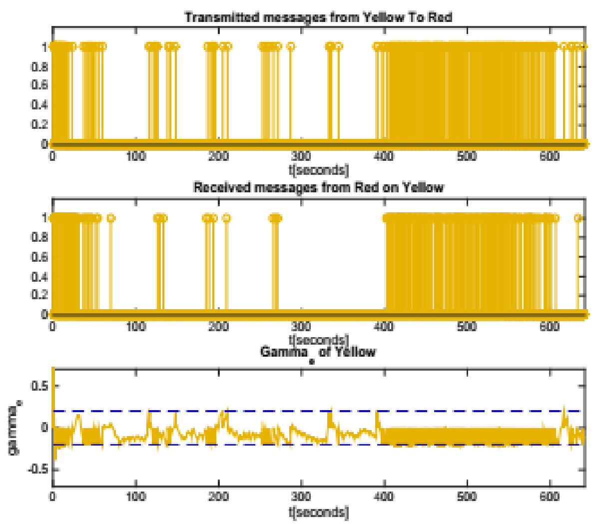
$$\epsilon = 0.2\text{m}$$



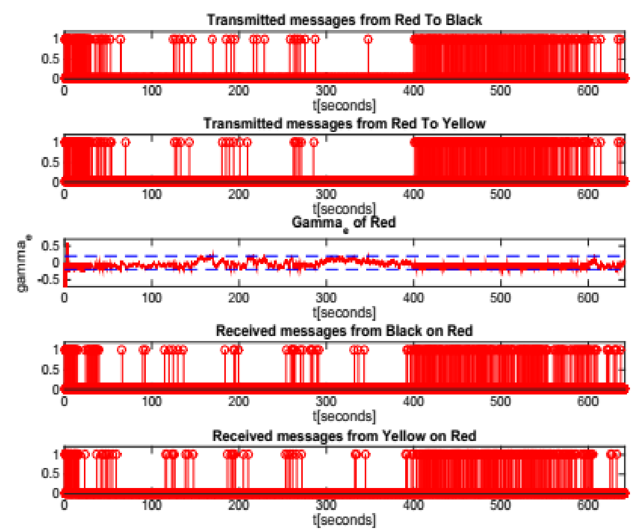




(a) Communication signal on Black vehicle

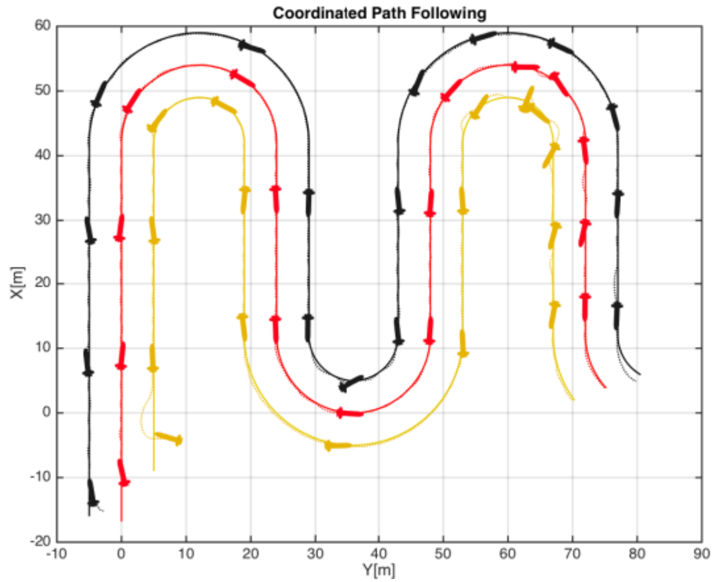


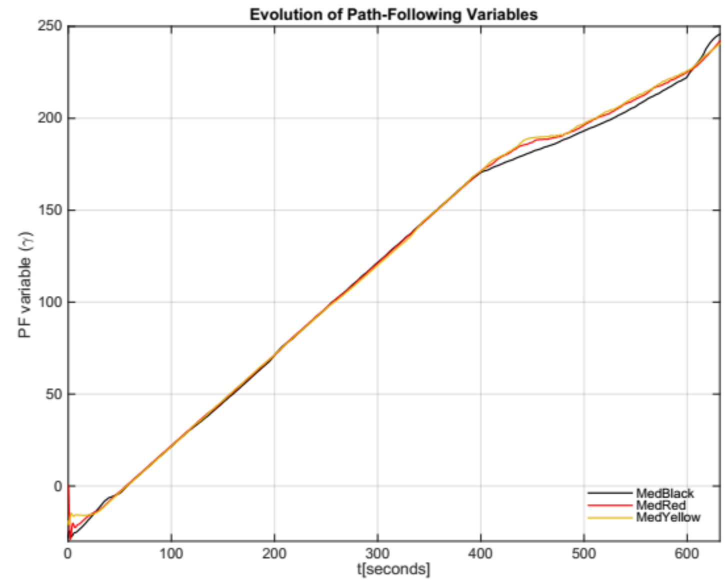
(b) Communication signal on Yellow vehicle

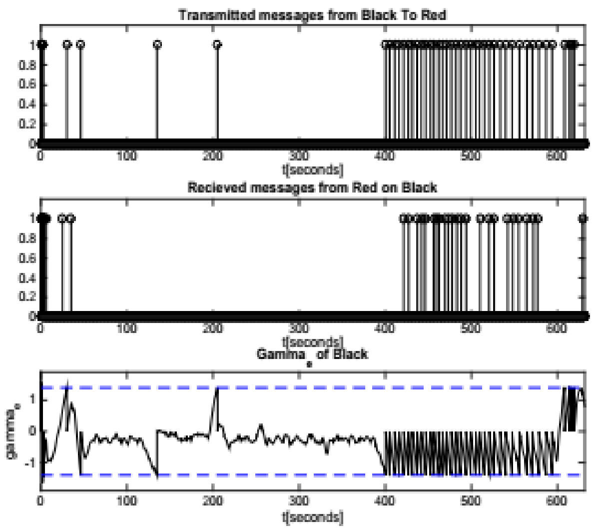


(c) Communication signal on Red vehicle

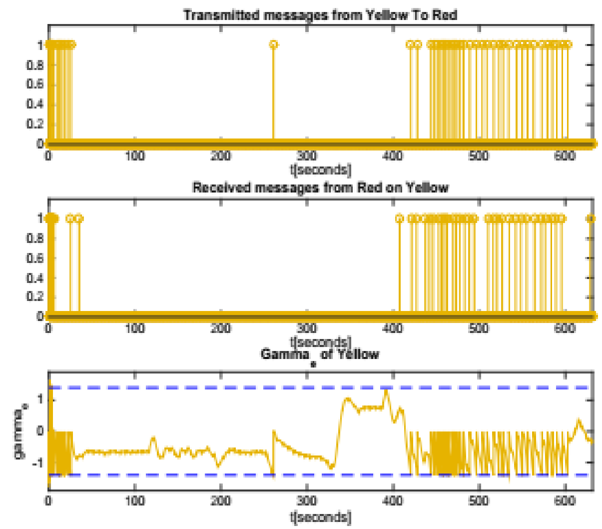
$\epsilon = 1.4\text{m}$



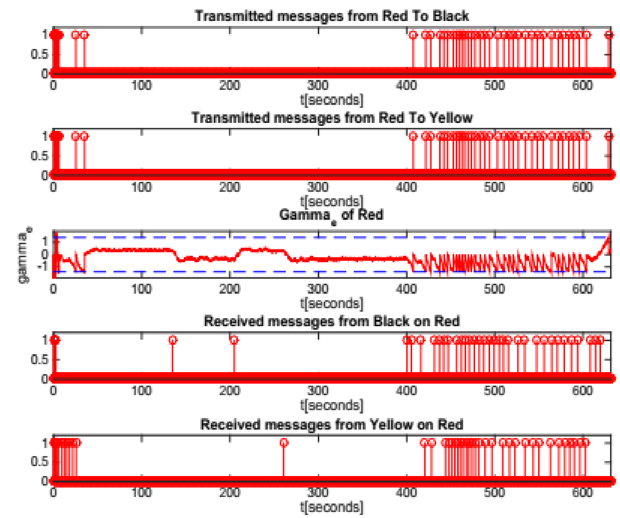




(a) Communication signal on Black vehicle



(b) Communication signal on Yellow vehicle



(c) Communication signal on Red vehicle

Outline

Future work:

1. Test Cooperative Path Following with the proposed Event Trigger Communication with Path Following Method 2.
2. Investigate the case when the communications channel has delays and exhibits packet losses.
3. Test the proposed Cooperative Path Following algorithm underwater, with acoustic and optical communications (using the multi-agent network developed in the WiMUST project).

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Thank you!

ISR/IST Team

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