Cooperative control of autonomous vehicles: theory and applications

Nguyen T. Hung

Contact: nguyen.hung@tecnico.ulisboa.pt

Institute for Systems and Robotics (ISR), Instituto Superior Tecnico (IST), University of Lisbon

VNCR seminar, July 2020

Institute for Systems and Robotics Lisboa

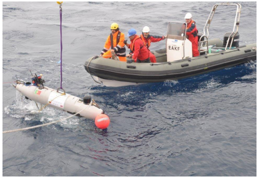
TÉCNICO LISBOA

U LISBOA

IST Lisbon and DSOR group

IST campus, viewed from Alameda park

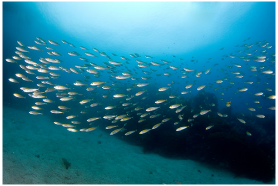
DSOR group



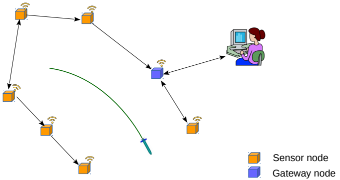
Multi agent systems (MAS) ▷ Examples

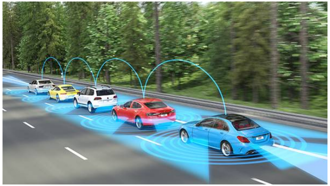
Nature behaviors





Engineering applications

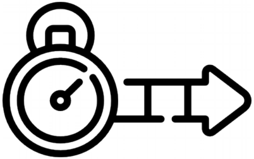




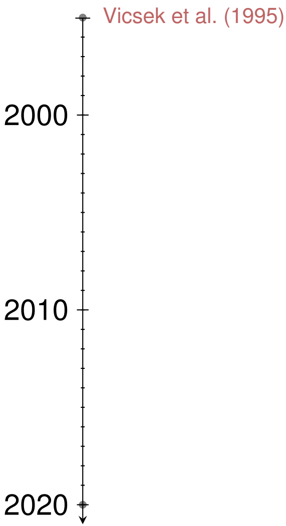

What next?

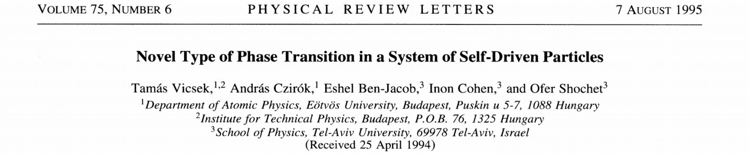
1. A brief review
2. Cooperative of MAS with event-triggered communications
3. Applications in cooperative control of autonomous vehicles
4. Others applications

A brief review



Cooperative control of MAS ▷ A brief review



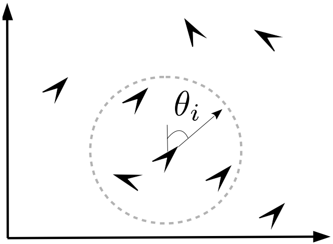


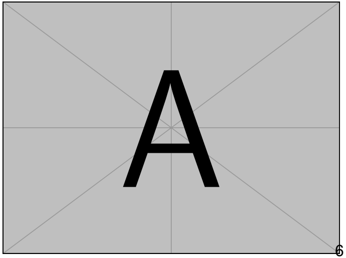
VOLUME 75, NUMBER 6 PHYSICAL REVIEW LETTERS 7 AUGUST 1995

Novel Type of Phase Transition in a System of Self-Driven Particles

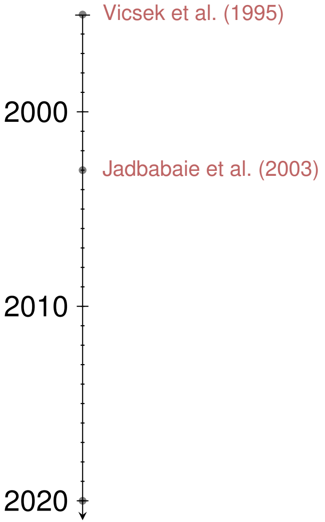
Tamás Vicsek,[1,2] András Czirók,[1] Eshel Ben-Jacob,[3] Inon Cohen,[3] and Ofer Shochet[3]
[1]*Department of Atomic Physics, Eötvös University, Budapest, Puskin u 5-7, 1088 Hungary*
[2]*Institute for Technical Physics, Budapest, P.O.B. 76, 1325 Hungary*
[3]*School of Physics, Tel-Aviv University, 69978 Tel-Aviv, Israel*
(Received 25 April 1994)

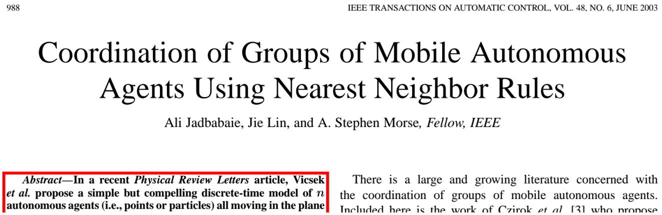
$$\theta_i(t+1) = \frac{1}{1+|\mathcal{N}_i(t)|}\Big(\theta_i(t) + \sum_{j\in\mathcal{N}_i(t)} \theta_j(t)\Big)$$





Cooperative control of MAS ▷ A brief review





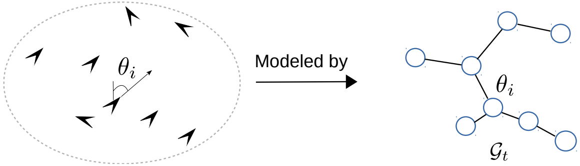
988 IEEE TRANSACTIONS ON AUTOMATIC CONTROL, VOL. 48, NO. 6, JUNE 2003

Coordination of Groups of Mobile Autonomous Agents Using Nearest Neighbor Rules

Ali Jadbabaie, Jie Lin, and A. Stephen Morse, *Fellow, IEEE*

***Abstract*—In a recent *Physical Review Letters* article, Vicsek *et al.* propose a simple but compelling discrete-time model of n autonomous agents (i.e., points or particles) all moving in the plane**

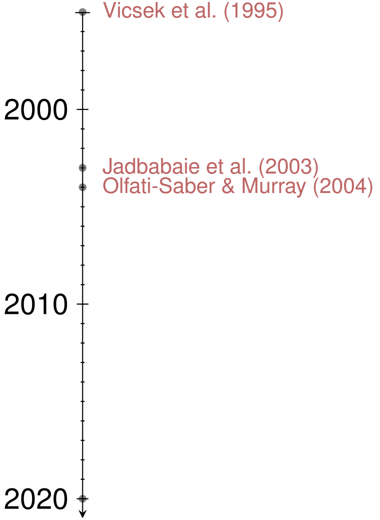
There is a large and growing literature concerned with the coordination of groups of mobile autonomous agents. Included here is the work of Czirok *et al.* [3] who propose



Result (Thm 1, Jadbabaie et al. (2003), roughly speaking)

If $\mathcal{G}_t$ is undirected, and connected $\forall t$, then $\lim_{t\to\infty} \theta_i(t) = \theta_{ss} \quad \forall i$

Cooperative control of MAS ▷ A brief review



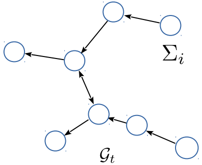
1520 IEEE TRANSACTIONS ON AUTOMATIC CONTROL, VOL. 49, NO. 9, SEPTEMBER 2004

Consensus Problems in Networks of Agents With Switching Topology and Time-Delays

Reza Olfati-Saber, *Member, IEEE*, and Richard M. Murray, *Member, IEEE*

- Average consensus problem

$$\Sigma_i : \quad \dot{x}_i = u_i, \quad i = 1, \ldots, N$$
$$u_i = -\sum_{j \in \mathcal{N}_i(t)} (x_i - x_j).$$

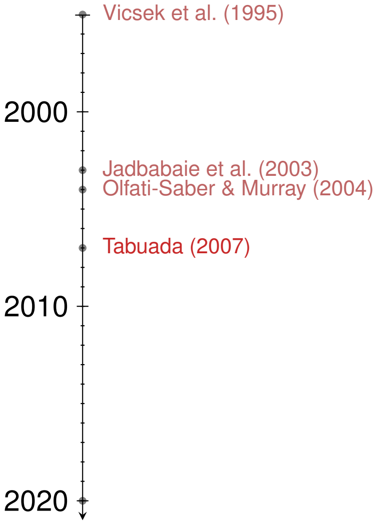


Result (Thm 9, Olfati-Saber & Murray (2004))

If $\mathcal{G}_t$ is strongly connected and balanced $\forall t$, then

$$\lim_{t \to \infty} x_i(t) = \sum_{i=1}^{N} x_i(0)/N, \qquad \forall i$$

Cooperative control of MAS ▷ A brief review

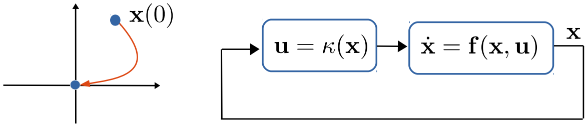


1680 IEEE TRANSACTIONS ON AUTOMATIC CONTROL, VOL. 52, NO. 9, SEPTEMBER 2007

Event-Triggered Real-Time Scheduling of Stabilizing Control Tasks

Paulo Tabuada, *Senior Member, IEEE*

tasks run for longer amounts of time using anytime implementations or model predictive controllers; or by scheduling control tasks more frequently. All these approaches assume the existence of a performance criterion for the control task such as a cost function used to design an



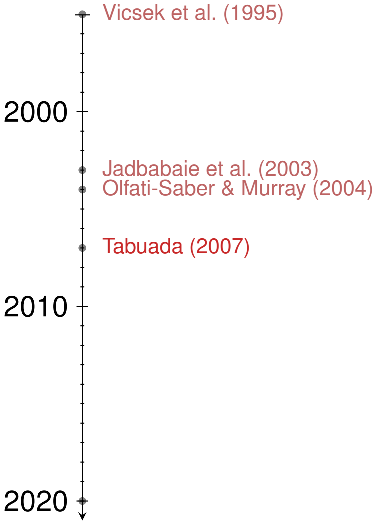
- Idea: Only update **u** when **x** changes ”significantly”.

Continuous control

- $\mathbf{u}(t) = \kappa(\mathbf{x}(t))$

Event-triggered control

- $\mathbf{u}(t) = \kappa(\mathbf{x}(t_k)), \quad t \in [t_k, t_{k+1})$
- if $\|\mathbf{x}(t) - \mathbf{x}(t_k)\| \geq \text{Threshold}$, $\mathbf{x}(t_{k+1}) := \mathbf{x}(t)$.



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Example:

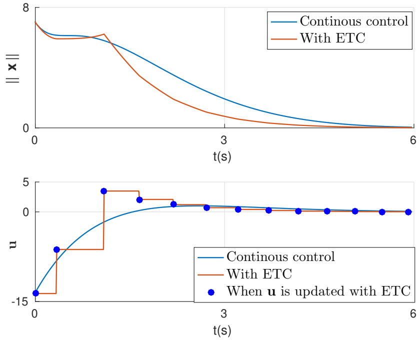
$$\dot{\mathbf{x}} = A\mathbf{x} + B\mathbf{u},$$

$$A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

$$\kappa(\mathbf{x}) = -K\mathbf{x}$$

with $K = [1, 1.7]$

$\text{Threshold} = 0.8\|\mathbf{x}(t)\|$



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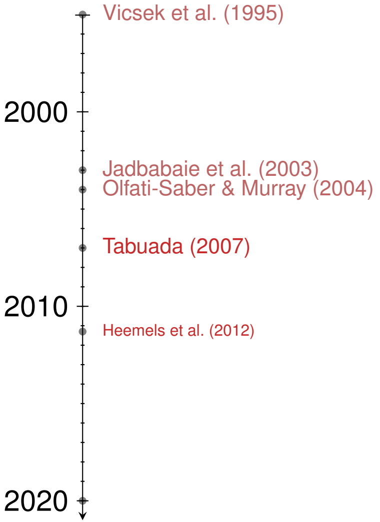
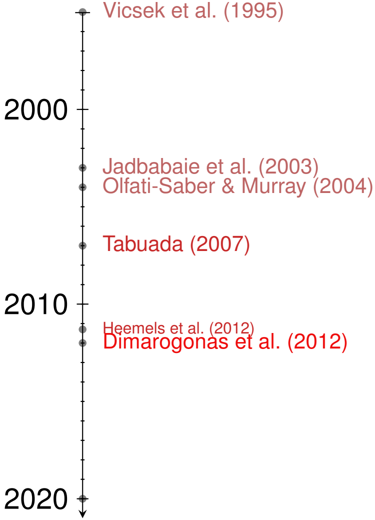


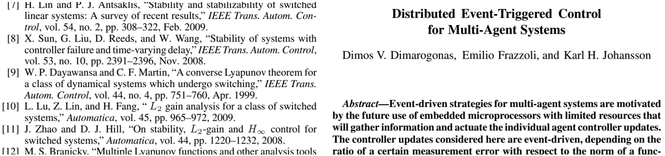
51st IEEE Conference on Decision and Control
December 10-13, 2012. Maui, Hawaii, USA

An Introduction to Event-triggered and Self-triggered Control

W.P.M.H. Heemels K.H. Johansson P. Tabuada

A nice tutorial about event triggered control and estimation!!!





[7] H. Lin and P. J. Antsaklis, "Stability and stabilizability of switched linear systems: A survey of recent results," *IEEE Trans. Autom. Control*, vol. 54, no. 2, pp. 308–322, Feb. 2009.
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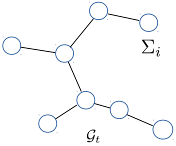
Distributed Event-Triggered Control for Multi-Agent Systems

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

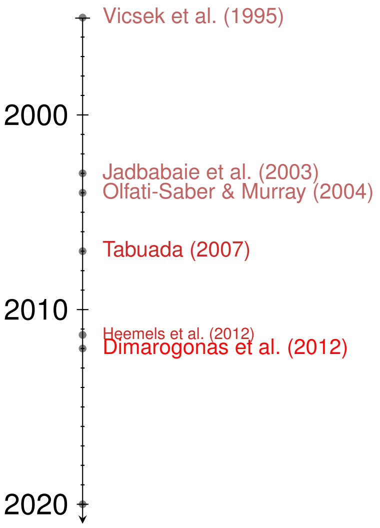
***Abstract*—Event-driven strategies for multi-agent systems are motivated by the future use of embedded microprocessors with limited resources that will gather information and actuate the individual agent controller updates. The controller updates considered here are event-driven, depending on the ratio of a certain measurement error with respect to the norm of a func-**



- Apply idea in Tabuada (2007) for consensus problem

$$\Sigma_i : \quad \dot{x}_i = u_i, \quad i = 1, ..., N.$$

- A mechanism to decide when u_i should be updated.



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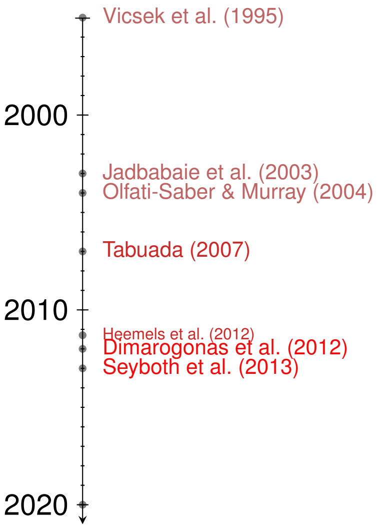
- Consensus control law

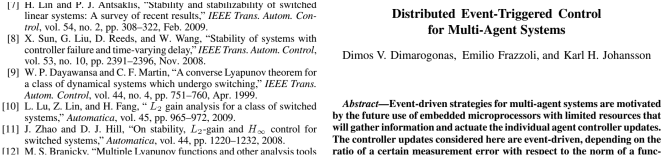
$$u_i = -\sum_{j \in \mathcal{N}_i} (\hat{x}_i(t) - \hat{x}_j(t))$$

where $\hat{x}_i(t) = \hat{x}_i(t_{i,k}) \quad \forall t \in (t_{i,k}, t_{i,k+1})$

- update u_i when

$$|\hat{x}_i(t) - x_i(t)| \geq c \left(\sum_{j \in \mathcal{N}_i} x_i(t) - x_j(t) \right)^2$$





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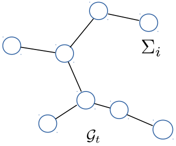
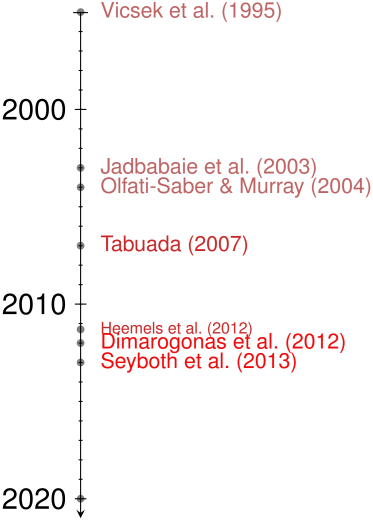
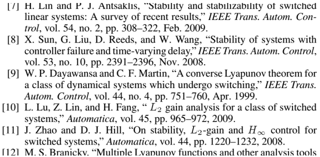


- Apply idea in Tabuada (2007) for consensus problem

$$\Sigma_i: \quad \dot{x}_i = u_i, \quad i = 1, \ldots, N.$$

- ETC decides when agents broadcast

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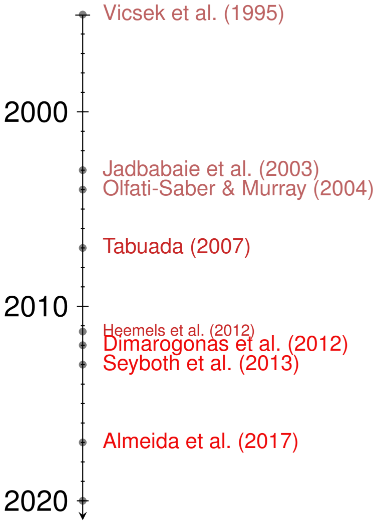
where $\hat{x}_i(t) = \hat{x}_i(t_{i,k}) \quad \forall t \in (t_{i,k}, t_{i,k+1})$

- Broadcast x_i when

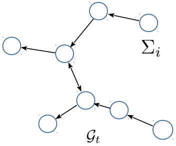
$$|\hat{x}_i(t) - x_i(t)| \geq h_i(t)$$



Transaction Automatic Control 2017

Synchronization of multi-agent systems using event-triggered and self-triggered broadcasts

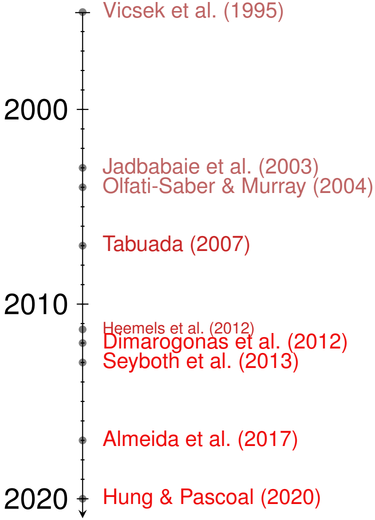
João Almeida, Carlos Silvestre, and António M. Pascoal



- ET-broadcast for synchronizing MAS

$$\Sigma_i : \quad \dot{\mathbf{x}}_i = A\mathbf{x}_i + \mathbf{u}_i, \quad i = 1, ..., N.$$

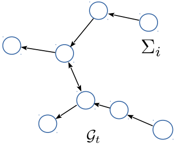
- ET-broadcast decides when agents broadcast their information (state).



International Journal of Control 2020, to appear

Consensus/synchronization of networked nonlinear multiple agent systems with event-triggered communications

Nguyen T. Hung[a] and Antonio M. Pascoal[a]

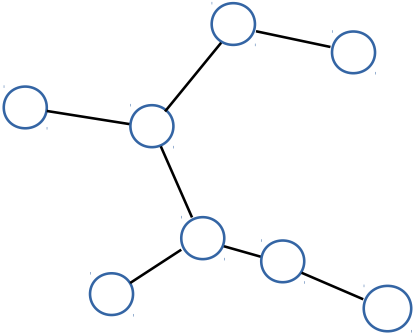


- ET-broadcast for synchronizing MAS

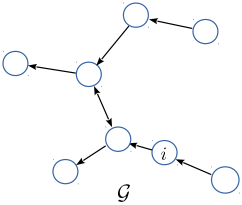
$$\Sigma_i: \quad \dot{\mathbf{x}}_i = A\mathbf{x}_i + \mathbf{f}(\mathbf{x}_i, t) + B\mathbf{u}_i, \quad i = 1, ..., N.$$

- ET-broadcast decides when agents broadcast their information (state).

Cooperative of MAS with event-triggered communications



A multi agent system with N agents:



$$\Sigma_i : \quad \dot{\mathbf{x}}_i = A\mathbf{x}_i + \mathbf{f}(\mathbf{x}_i, t) + B\mathbf{u}_i, \quad i = 1, \ldots, N,$$

Asm: $\mathbf{f}(\mathbf{x}, t)$ is Lipschitz in $\mathbf{x}$.

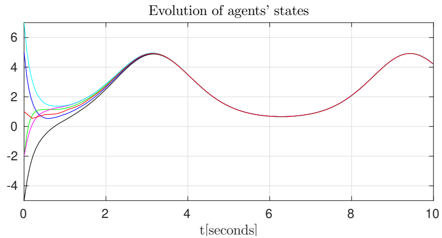
Problem (Consensus/synchronization)

Find $\mathbf{u}_i(\mathbf{x}_i, \mathbf{x}_j); j \in \mathcal{N}_i^{\mathrm{in}\,a}$ *s.t.*

- $\lim_{t\to\infty} \mathbf{x}_i(t) - \mathbf{x}_j(t) = 0,$
- $\lim_{t\to\infty} \dot{\mathbf{x}}_i = A\mathbf{x}_i + \mathbf{f}(\mathbf{x}_i, t),$

$\forall i, j = 1, \ldots N.$

[a] set of neighbors where i can receive information

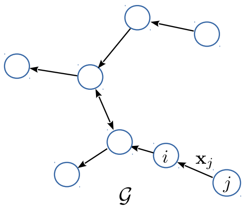


Distributed control law:

$$\mathbf{u}_i = cK \sum_{j \in \mathcal{N}_i^{\text{in}}} \mathbf{x}_i - \mathbf{x}_j \qquad (1)$$

Feedback gains

From in-neighbors



Result (Li et al. (2012))

The consensus/synchronization problem is solved with protocol (1) *if*

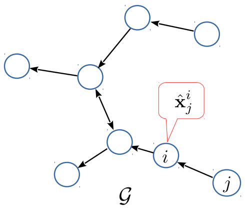
- c, K *are chosen properly and*
- $\mathcal{G}$ *is strongly connected.*

Consensus/synchronization of MAS with ETC ▷ Concept

Distributed control law:

$$\mathbf{u}_i = cK \sum_{j \in \mathcal{N}_i^{\text{in}}} \mathbf{x}_i - \hat{\mathbf{x}}_j^i \qquad (2)$$

estimated neighbor's state



$$\hat{\mathbf{x}}_j^i : \begin{cases} \dot{\hat{\mathbf{x}}}_j^i = A\hat{\mathbf{x}}_j^i + \mathbf{f}(\hat{\mathbf{x}}_j^i, t) \\ \hat{\mathbf{x}}_j^i(t_{ij,k}^+) = \mathbf{x}_j(t_{j,k}) \end{cases} \qquad (3)$$

Time instant at which i recieves

Time instant at which j broadcasts

$$\mathbf{e}_j \triangleq \hat{\mathbf{x}}_j^i - \mathbf{x}_j$$

$$(2) \Leftrightarrow \quad \mathbf{u}_i = cK \sum_{j \in \mathcal{N}_i^{\text{in}}} \mathbf{x}_i - \mathbf{x}_j + \mathbf{e}_j$$

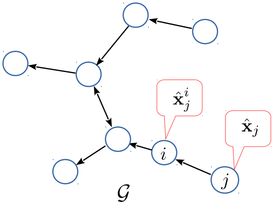
- $\mathbf{e}_j$: the estimation error of j at i.
- Our wish: If $\mathbf{e}_j$ "big", j must transmit the latest of $\mathbf{x}_j$ to i to update $\hat{\mathbf{x}}_j^i$. But how?

Consensus/synchronization of MAS with ETC ▷ Concept

Distributed control law:

$$\mathbf{u}_i = cK \sum_{j \in \mathcal{N}_i^{\text{in}}} \mathbf{x}_i - \hat{\mathbf{x}}_j^i \qquad (2)$$

estimated neighbor's state



$$\hat{\mathbf{x}}_j^i : \begin{cases} \dot{\hat{\mathbf{x}}}_j^i = A\hat{\mathbf{x}}_j^i + \mathbf{f}(\hat{\mathbf{x}}_j^i, t) \\ \hat{\mathbf{x}}_j^i(t_{ij,k}^+) = \mathbf{x}_j(t_{j,k}) \end{cases} \qquad (3)$$

Time instant at which i recieves

Time instant at which j broadcasts

$$\hat{\mathbf{x}}_j : \begin{cases} \dot{\hat{\mathbf{x}}}_j = A\hat{\mathbf{x}}_j + \mathbf{f}(\hat{\mathbf{x}}_j, t) \\ \hat{\mathbf{x}}_j^i(t_{j,k}^+) = \mathbf{x}_j(t_{j,k}) \end{cases} \qquad (4)$$

If there is no communication delay:

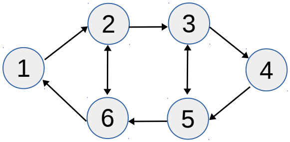
$$\hat{\mathbf{x}}_j^i(t) = \hat{\mathbf{x}}_j(t) \quad \Rightarrow \quad \mathbf{e}_j(t) = \mathbf{x}_j(t) - \hat{\mathbf{x}}_j(t) \quad \forall t.$$

Monitor $\mathbf{e}_j(t)$ and broadcast $\mathbf{x}_j(t)$ whenever

A designed threshold

$$\|\mathbf{e}_j(t)\| \geq h_j(t).$$

A multi agent system with 6 agents:

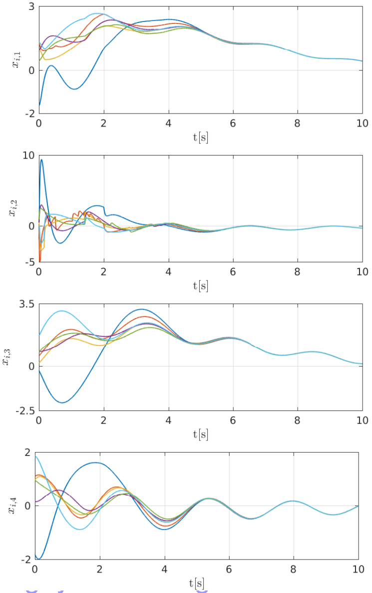


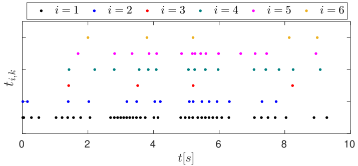
$$\Sigma_i : \quad \dot{\mathbf{x}}_i = A\mathbf{x}_i + \mathbf{f}(\mathbf{x}_i, t) + B\mathbf{u}_i, \quad i = 1, ..., N,$$

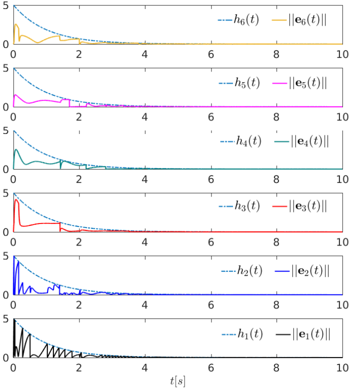
$$\mathbf{x}_i = [x_{i1}, x_{i2}, x_{i3}, x_{i4}]^{\mathrm{T}}.$$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -2 & -1 & 2 & 0 \\ 0 & 0 & 0 & 2 \\ 1.95 & 0 & -1.95 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0 & 1 & 0 & 0 \end{bmatrix}^{\mathrm{T}}, \quad \mathbf{f}(\mathbf{x}_i, t) = [0\ 0\ 0\ -0.333 \sin(x_{i3})]^{\mathrm{T}}$$

Consensus/synchronization of MAS with ETC ▷ Illustrative examples





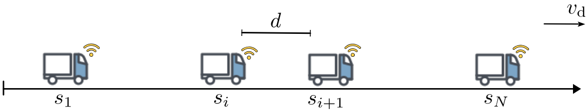


Applications in cooperative control of autonomous vehicles

Vehicle platooning

Vehicle model:

$$\dot{s}_i = v_i, \quad \forall i = 1, ..., N \qquad (5)$$



Change coordinate: For $\forall i = 1, N$

$$x_i \triangleq s_i - (i-1)d, \qquad v_i \triangleq v_\mathrm{d}(t) + u_i.$$

$$(5) \Leftrightarrow \quad \dot{x}_i = v_\mathrm{d}(t) + u_i, \quad \forall i = 1, ..., N.$$

Problem (original)

Find $v_i(s_i, s_j); j \in \mathcal{N}_i$[a] *s.t.*

- $\lim_{t\to\infty} s_{i+1}(t) - s_i(t) = d$, $\forall i = 0, ..., N-1$.
- $\lim_{t\to\infty} \dot{s}_i = v_\mathrm{d}(t)$, $\forall i = 1, ...N$.

[a] $\mathcal{N}_i \triangleq \{i-1, i+1\}$

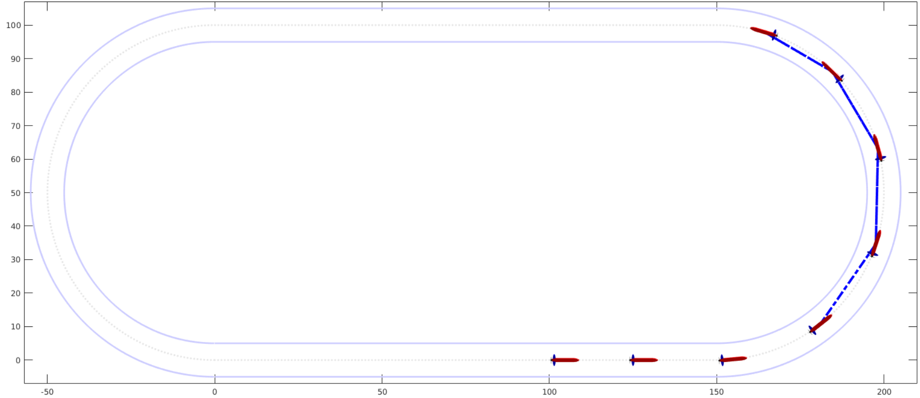
Problem (reformulated)

Find $u_i(x_i, x_j); j \in \mathcal{N}_i$ *s.t.*

- $\lim_{t\to\infty} x_i(t) - x_j(t) = 0$,
- $\lim_{t\to\infty} \dot{x}_i = v_\mathrm{d}(t)$,

$\forall i = 1, ...N$.

Vehicle platooning



Cooperative path following (CPF)

Problem formulation

Vehicle i – V_i:

Rot. matrix $\{\mathcal{B}^{[i]}\}$ to $\{\mathcal{I}\}$

$$\dot{\mathbf{p}}^{[i]} = R(\boldsymbol{\eta}^{[i]})\mathbf{v}^{[i]},$$
$$\dot{\boldsymbol{\eta}}^{[i]} = T(\boldsymbol{\eta}^{[i]})\boldsymbol{\omega}^{[i]}$$

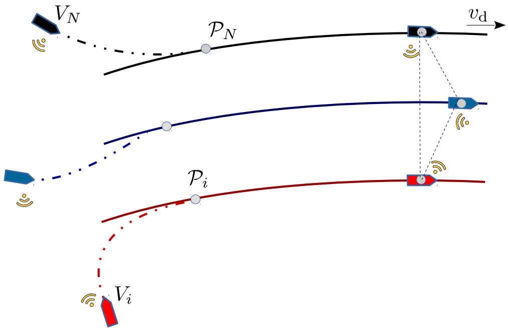
Orientation vector

Path i – $\mathcal{P}_i$:

$$\mathbf{p}_{\mathrm{d}}^{[i]} : \gamma^{[i]} \to \mathbf{p}_{\mathrm{d}}^{[i]}(\gamma^{[i]})$$

path parameterizing variable

(e.g. path length)



Cooperative path following (CPF)

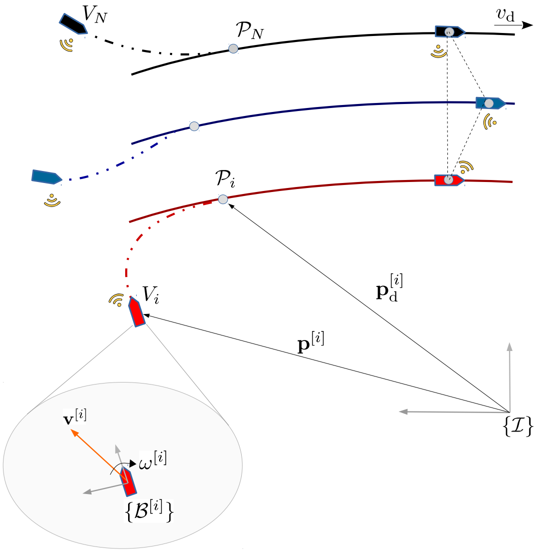
Problem formulation

Problem (CPF)

Find $\mathbf{v}^{[i]}, \omega^{[i]}, \dot{\gamma}^{[i]}$ *to fulfill*

1. *Path following task:*
   - $\mathbf{p}^{[i]}(t) \to \mathbf{p}_{\mathrm{d}}^{[i]}(\gamma^{[i]}(t))$
2. *Cooperative task:*
   - $\gamma^{[i]}(t) \to \gamma^{[j]}(t), \qquad \forall i, j$
   - $\dot{\gamma}^{[i]}(t) \to v_{\mathrm{d}}, \qquad \forall i$

as $t \to \infty$.



Cooperative path following (CPF)

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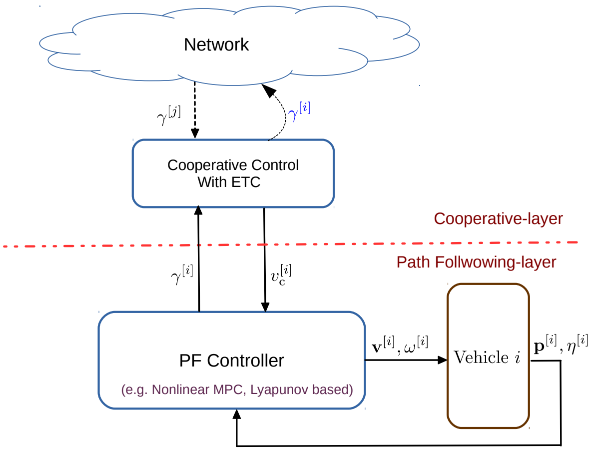
as $t \to \infty$.

CPF control system for V_i [a]

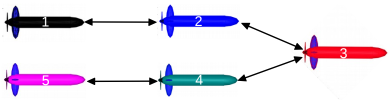


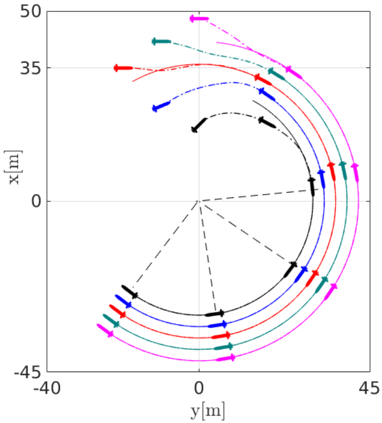
[a] Rego et al. (2019), Hung et al. (2020)

CPF - simulation examples

Setup (Hung et al. (2020))

- 5 constrained under-actuated vehicles
- PF controller: Nonlinear MPC

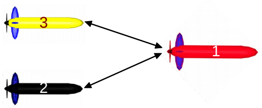


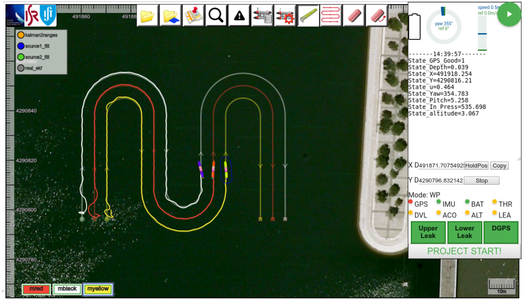


CPF - real tests

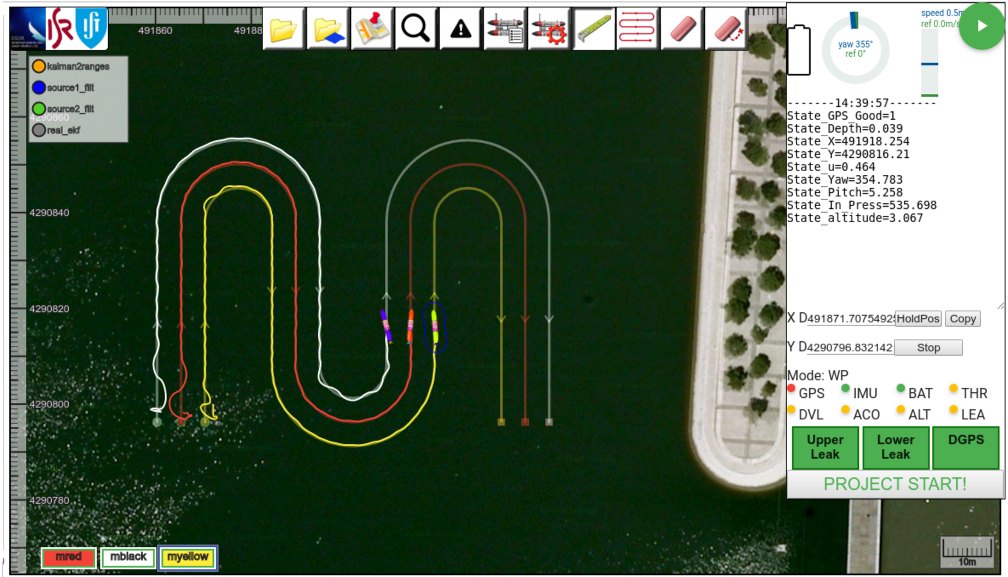
Setup (Rego et al. (2019))

- 3 Medusa class AUVs
- PF controller: Lyapunov based controller





CPF - real tests



CPF - real tests

Setup Rego et al. (2019)

- 3 Medusa class AUVs
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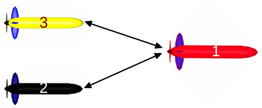
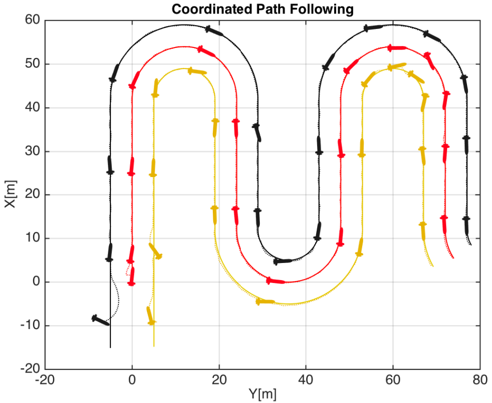
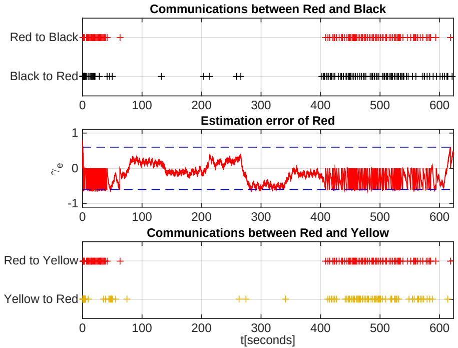


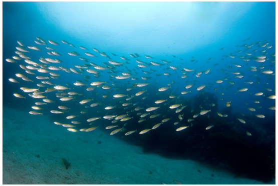




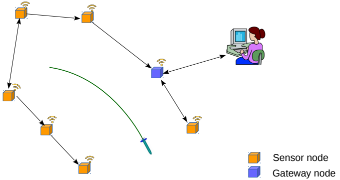
Others applications

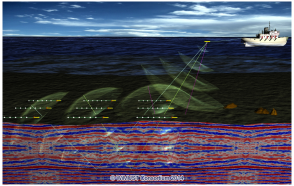
Other applications

To learn (model) nature's behaviors



Engineering applications





Thank you!

Other videos:

Wimust project: click here.
US navy: click here.

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