Cooperative Path Following of Robotic Vehicles using Event based Control and Communication

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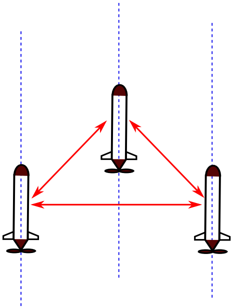
Outline of Presentation

Introduction

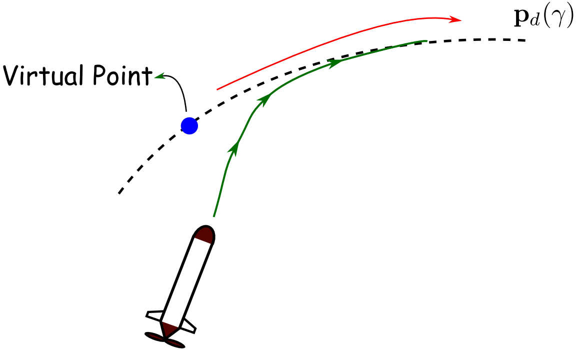


Continuous inter-robot communication!

1. Practical? Considering...
   - Communication hardware.
   - Bandwidth and Power
2. Necessary?

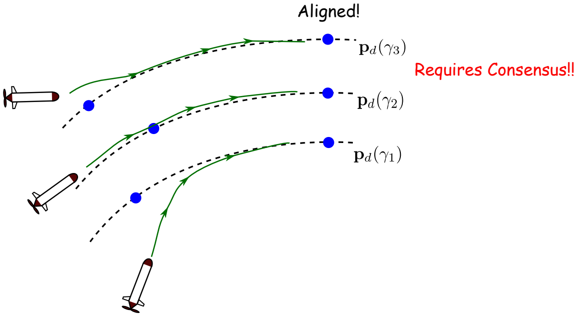
- Need for methods that reduce frequency of communication between the robots!
- Event-triggered Consensus and Self-triggered Consensus algorithms applied to the Cooperative Path Following (CPF) problem.

Cooperative Path Following Framework



- A two stage control architecture.
- Lower layer: Path Following (PF) controller.
  1. Responsible for motion control of individual robot.
  2. Follows a pre-specified geometric path (no temporal constraints)

Cooperative Path Following Framework



- Higher layer: Cooperative Controller (CC)
  1. Responsible for cooperation among multiple robots.
  2. First order Consensus controller.
  3. **Main results:** Self-triggered approach[1] and Event-triggered approach[2]

[1] Jain, R. Praveen, A. Pedro Aguiar, and João Borges de Sousa. "Self-triggered cooperative path following control of fixed wing Unmanned Aerial Vehicles." In International Conference on Unmanned Aircraft Systems (ICUAS), pp. 1231-1240. IEEE, 2017.

[2] Jain, R. Praveen, A. Pedro Aguiar, and João Borges de Sousa. "Cooperative Path Following of Robotic Vehicles using an Event based Control and Communication Strategy." Accepted to the International Conference on Robotics and Automation (ICRA), 2018.

Path Following Control Design

System Model

Assumptions

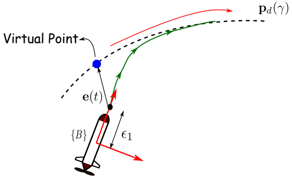
1. 2D operation, extension to 3D case straight forward.
2. Inner loop controller able to track the reference control commands generated by the PF controller.

System Model

$$\dot{\mathbf{p}}_i(t) = R_i(t)\mathbf{v}_i(t) + \mathbf{w}_i(t)$$
$$\dot{R}_i(t) = R_i(t)S(\boldsymbol{\omega}_i)$$

where $\mathbf{p}_i \in \mathbb{R}^2$ - position of the robot w.r.t inertial frame $\{\mathrm{I}\}$, $\mathbf{v}_i \in \mathbb{R}^2 = [v_{f_i} \;\; 0]^T$ - linear velocity of the robot w.r.t body frame $\{\mathrm{B}\}$, $R_i \in SO(2)$, $S(\omega_i(t)) \in so(2)$ and $\omega_i \in \mathbb{R}$ is input angular velocity, $\mathbf{u}_i(t) = [v_{f_i} \;\; \omega_i]^T$ - control inputs for the vehicle,

Problem Formulation



- Consider a given reference geometric path $\mathbf{p}_{d_i}(\gamma_i) : \mathbb{R} \rightarrow \mathbb{R}^2$ parameterized by the path variable $\gamma_i \in \mathbb{R}$.
- A desired speed assignment $v_d \in \mathbb{R}$.

Control Objective

- Design $\mathbf{u}_i(t)$ such that the path following error, $\|\mathbf{p}_i - \mathbf{p}_{d_i}(\gamma_i)\|$ converges to an arbitrary small neighborhood of the origin as $t \rightarrow \infty$.
- The desired speed assignment, $\|\dot{\gamma}_i - v_d\| \rightarrow 0$ as $t \rightarrow \infty$.

Error Dynamics

- Define error variable

$$\mathbf{e}_i = R_i^T(\mathbf{p}_i - \mathbf{p}_{d_i}(\gamma_i)) + \boldsymbol{\epsilon}$$

- The error dynamics satisfies

$$\dot{\mathbf{e}}_i = -S(\omega_i)\mathbf{e}_i + \Delta\mathbf{u}_i - R_i^T \frac{\partial \mathbf{p}_{d_i}(\gamma_i)}{\partial \gamma_i}\dot{\gamma}_i$$

where $\Delta = \begin{bmatrix} 1 & -\epsilon_2 \\ 0 & \epsilon_1 \end{bmatrix}$, $\mathbf{u}_i = [v_{f_i} \;\; \omega_i]^T$ and $\boldsymbol{\epsilon} = [\epsilon_1 \;\; \epsilon_2]^T \neq 0$.

- Impose

$$\dot{\gamma}_i = v_d + \tilde{v}_r^i + g_i(t)$$

where $\tilde{v}_r^i$ is additional control input used for achieving cooperation and $g_i(t)$ is the path following error correction term with $\|g_i(t)\| \leq \mu$

A. Alessandretti, A. P. Aguiar and C. N. Jones, "Trajectory-tracking and path-following controllers for constrained underactuated vehicles using Model Predictive Control," 2013 European Control Conference (ECC), Zurich, 2013, pp. 1371-1376.

Control Law

Theorem: Path Following Controller

Given the error dynamics for the path following system, the estimate of error states $\hat{\mathbf{e}}_i(t) = \mathbf{e}_i(t) + \tilde{\mathbf{e}}_i(t)$, the control law

$$\mathbf{u}_i = \Delta^{-1}\left(-K_p\hat{\mathbf{e}}_i + R_i^T \frac{\partial \mathbf{p}_{d_i}(\gamma_i)}{\partial \gamma_i} v_d\right)$$

makes the closed-loop system Input-to-State Stable (ISS) with respect to the estimation error $\tilde{\mathbf{e}}_i(t)$, the formation speed actuation signal $\tilde{v}_r^i(t)$ and path following error correction term $g_i(t)$.

Event based Cooperative Control

Control and Communication

Problem Formulation

- Consider N robots with associated reference path $\mathbf{p}_{d_i}(\gamma_i)$ parameterized by γ_i for $i = 1, 2, \cdots, N$.
- Let $\dot{\gamma}_i = v_d + \tilde{v}_r^i + g_i$.

Control Objective

Design decentralized, event-triggered control law for $\tilde{v}_r^i$ such that,

1. $\|\gamma_i - \gamma_j\| \to 0$ for all $i, j = 1, \cdots, N$ and $i \neq j$ as $t \to \infty$.
2. Each robot communicates and updates control action at event time instants t_k^i determined by an Event Triggering Condition

First Order Consensus

- Consider N agents modeled as single integrator dynamics

$$\dot{\gamma}_i = u_i(t)$$

- Known result on continuous time average consensus for undirected graphs:

$$u_i(t) = -\sum_{j \in \mathcal{N}_i} \gamma_i(t) - \gamma_j(t) = -L\boldsymbol{\gamma}(t)$$

where L is the graph Laplacian

Controller is implemented continuously!
Neighbor states are measured continuously!

Step 1: Event-triggered Consensus

Theorem: Event-triggered Consensus

The decentralized, event-triggered consensus controller

$$u_i(t) = -\sum_{j \in \mathcal{N}_i} (\gamma_i(t_k^i) - \gamma_j(t_k^i)) = [L\boldsymbol{\gamma}(t_k^i)]_i$$

defined over $t \in \bigcup_{k \in \mathbb{Z}_{\geq 0}} [t_k^i, t_{k+1}^i)$ along with the decentralized triggering condition

$$e_i^2 \leq \sigma_i \left(\sum_{j \in \mathcal{N}_i} \gamma_i(t) - \gamma_j(t) \right)^2$$

achieves consensus for the single integrator agents. Here $e_i(t) := [L\boldsymbol{\gamma}(t_k^i)]_i - [L\boldsymbol{\gamma}]_i$ and t_k^i is the event time for the agent i. $0 < \sigma_i < 1$ is the tuning parameter.

Event-based Cooperative Control

- Given the dynamics of path variable γ_i

$$\dot{\gamma}_i = v_d + \tilde{v}_r^i + g_i$$

- The results of event-triggered consensus (practical) hold in presence of v_d and g_i. That is,

$$\tilde{v}_r^i(t) = -\sum_{j \in \mathcal{N}_i} (\gamma_i(t_k^i) - \gamma_j(t_k^i))$$

  and

$$e_i^2 \leq \sigma_i \left(\sum_{j \in \mathcal{N}_i} \gamma_i(t) - \gamma_j(t) \right)^2$$

  achieves synchronization of path variables γ_i.

Continuous measurement (communication)!

Step 2: Event-based Communication

- For a generic agent i, define the communication packet

$$\mathcal{C}_i(t_k^i) := \left(t_k^i, \gamma_i(t_k^i), \tilde{v}_r^i(t_k^i), g_i(t_k^i)\right)$$

  Consequently, agent i receives $\mathcal{C}_j(t_{k_j(t)}^j)$ from $j \in \mathcal{N}_i$.

- $\tilde{v}_r^j(t)$ is held constant over the time interval $t \in [t_k^j, t_{k+1}^j)$ for all $j \in \mathcal{N}_i$. Hence, agent i estimates,

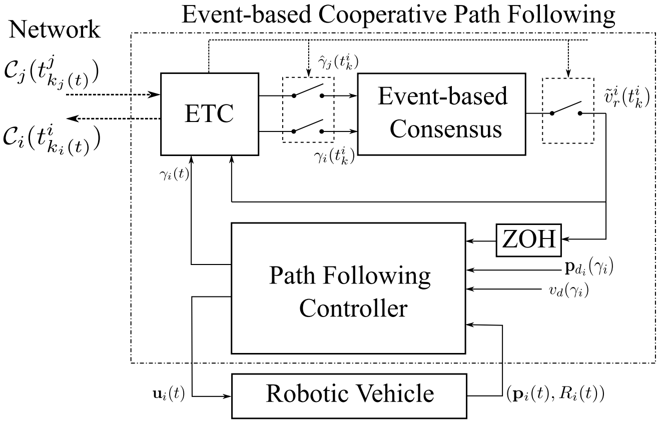
$$\hat{\gamma}_j(t) = \gamma_j(t_{k_j(t)}^j) + (t - t_{k_j(t)}^j)(v_d + \tilde{v}_r^j(t_{k_j(t)}^j)) + g_j(t_{k_j(t)}^j))$$

- Then event is generated on agent i using,

$$e_i^2(t) \leq \sigma_i \left(\sum_{j \in \mathcal{N}_i} \gamma_i(t) - \hat{\gamma}_j(t) \right)^2$$

Result: Event-based communication!

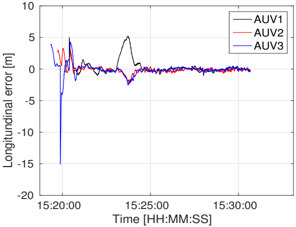
Event-based Cooperative Path Following

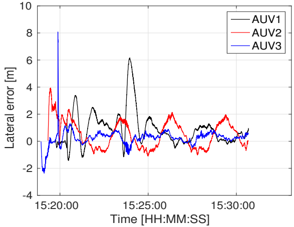


Cascade of two ISS subsystems!

Experiment Results

- Cooperative Path Following in circular paths using three AUVs
- Constant speed assignment of $v_d = 0.035$ [rad/s].
- Sampling frequency of 100 Hz.
- Gains of Path Following tuned manually, $\epsilon = [0.3 \;\; 0]^T$.





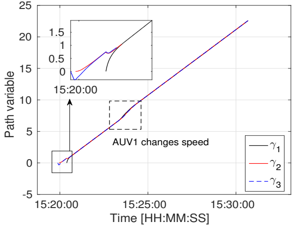
Experiment Results

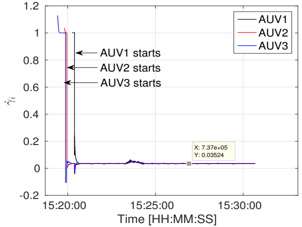
- Error between the path variable γ_i for $i = \{1, 2, 3\}$ of each AUV asymptotically converges to zero. Consensus!!

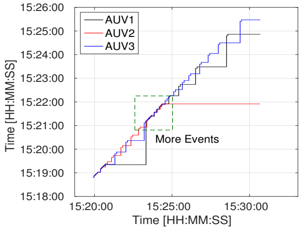
- $\dot{\gamma}_i \rightarrow v_d$. Desired speed assignment achieved.

Table 1 : Event time for Circular formation

	AUV-1	AUV-2	AUV-3
Duration [s]	617.96	643.48	648.17
Max τ_k [s]	160.24	32.10	78.80
Min τ_k [s]	0.70	0.03	0.61
Num Events	31	36	51
Periodic	61796	64348	64817
% Comms	0.050	0.055	0.078







Open Problems

You want to communicate, but cannot??

- Preliminary tests show that the proposed event-based method can tolerate communication losses.
- Formal investigation needed to analyze effects of communication/packet losses and communication delays.
- Delays can play important role in underwater acoustic communications.

Different Formation Control approaches??

- The current approach $\rightarrow$ Static formations!
- Can the formations be more dynamic?

Questions???