Cooperative Path Following with Logic Based Communication
From Theory to Real Experiment

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Outline

1. Introduction
2. Path Following
3. Coordination of Multi Agent System
4. Cooperative Path Following
5. Experimental Results
6. Conclusion and Future Directions
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INTRODUCTION

Where Cooperative Path Following used for?

“Go to Formation”

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

Why Logic Based Communication?

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**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.

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

What is Cooperative Path Following?

Set of $N \geq 2$ $N$ spatial paths

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

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

Set of vehicles

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

Objectives:

1. All vehicles converge to their assigned paths
2. Path parameters reach consensus, i.e
   $$\gamma^i(t) = \gamma^j(t) = ... = \gamma^N(t) \text{ as } t \rightarrow \infty$$
3. Path parameters run with a common desired speed profile
   $$\dot{\gamma}^1(t) = \dot{\gamma}^2(t) = ... = \dot{\gamma}^N(t) = v_d \text{ as } t \rightarrow \infty$$
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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 *,† Morten Breivik * Roger Skjetne *

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

L. Lapierre1,*,†, D. Soetanto2,‡ and A. Pascoal2,§

**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

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

Andrea Alessandretti1, 2, A. Pedro Aguiar3 and Colin N. Jones1
Path Following Controller - Method 1

\[ u_d = \begin{bmatrix} u \\ r \end{bmatrix} = \Delta^{-1} \left( -K(e - \delta) + R^T(\psi) \frac{\partial p_d(\gamma)}{\partial \gamma} v_d \right) \]

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

Then \( e = \delta \) is GAS.

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

Task: Stabilize the path following error
**Path Following Controller- Method 2**

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

$$u = v_d; \quad \dot{\gamma} = u \cos(\psi_e) + k_1 e_x$$

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

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 $e$ is GAS.

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

**Task:** Stabilize the path following error.
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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 asymptotically, i.e $\gamma^1(t) = \gamma^2(t) = \ldots = \gamma^N(t)$ as $t \to \infty$

Tools

Graph theory, Network Control

Consensus Protocols for Networks of Dynamic Agents

Reza Olfati Saber, Richard M. Murray
Control and Dynamical Systems
California Institute of Technology
Pasadena, CA 91125
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 $G(V, E)$ be the graph induced by the internetwork. $V$ is the set of vertices and $E$ 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.

\[ D = \{d_{ij}\} = \begin{cases} |N_i|, & \text{if } i = j \\ 0, & \text{otherwise} \end{cases} \]

\[ A = \{a_{ij}\} = \begin{cases} 1, & \text{if } j \in N_i \\ 0, & \text{otherwise} \end{cases} \]

$N_i$ : set of neighboring agents of agent $i^{th}$

$|N_i|$ : is the cardinality of $N_i$

\[
D = \begin{bmatrix}
3 & 0 & 0 & 0 \\
0 & 2 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 2 \\
\end{bmatrix}
\]

\[
A = \begin{bmatrix}
0 & 1 & 1 & 1 \\
1 & 0 & 0 & 1 \\
1 & 0 & 0 & 0 \\
1 & 1 & 0 & 0 \\
\end{bmatrix}
\]

\[
L = \begin{bmatrix}
3 & -1 & -1 & -1 \\
-1 & 2 & 0 & -1 \\
-1 & 0 & 1 & 0 \\
-1 & -1 & 0 & 2 \\
\end{bmatrix}
\]
**Fact**-[Properties of Laplacian matrix]
If the graph is undirected and connected

- $L$ is symmetric 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*

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

*The distributed control law for $v_c^{[i]}$ given by*

$$v_c^{[i]} = -k\left(\sum_{j \in N^{[i]}} \gamma^{[i]} - \gamma^{[j]}\right) \text{ for all } i \in N$$

*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.*
With logic based communication, new coordination control law

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

where

\[ \hat{\gamma}^{[j]}(t) = v_d \text{ for } t_k \leq t \leq t_{k+1} \text{ and } \hat{\gamma}^{[j]}(t^{[j]}) = \gamma^{[j]}(t_{k}^{[j]}), j \in \mathcal{N}^{[i]} \]

\[ \hat{\gamma}^{[i]}(t) = v_d \text{ for } t_k \leq t \leq t_{k+1} \text{ and } \hat{\gamma}^{[i]}(t^{[i]}) = \gamma^{[i]}(t_{k}^{[i]}) \]

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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Result 1:
CPF system is ISS respect to the error of estimation of the path parameters, which is bounded by $\varepsilon$, 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 $\varepsilon$, 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
EXPERIMENTAL RESULTS

- Surface and diving versions: MEDUSAₘ and MEDUSAₙ
- Two-body shape, 30 kg, easy launch & recovery
- Depths up to 50 m
- Five units built since 2009
EXPERIMENTAL RESULTS

Medusa Class Vehicles

The MEDUSA vehicles
• Network Topology: undirected
• Communication medium: wifi
EXPERIMENTAL RESULTS

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**: \( v_d = 0.5 \text{m/s} \)

**Path following controller**: Method 1

**Periodic communication time**: 0.2s
$\epsilon = 0.2\text{m}$
\( \epsilon = 1.4 \text{m} \)
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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).
Thank you!

ISR/IST Team

Francisco Rego, António Pascoal, João Botelho, Jorge Ribeiro, Miguel Ribeiro, Manuel Rufino, Luís Sebastião, Henrique Silva