LIRMM
Laboratoire d'Informatique de Robotique et de Microélectroniqu de Montpellier
UM2 UNIVERSITÉ MONTPELLIER 2 SCIENCES ET TECHNIQUES
CNRS
FREEsubNET
RESEARCH
MARIE CURIE ACTIONS

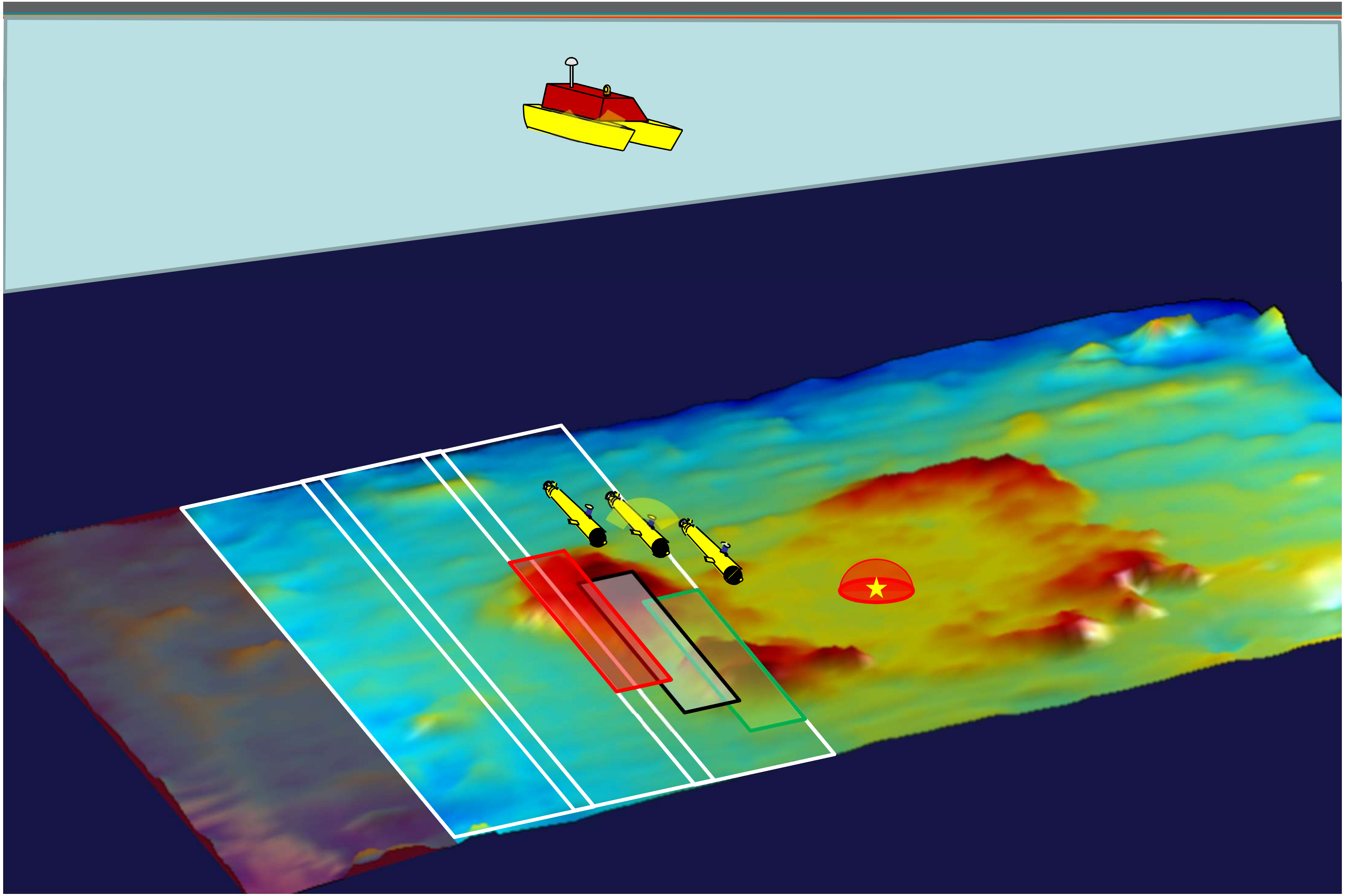
Coordinated motion control of underactuated autonomous underwater vehicles

Xianbo XIANG

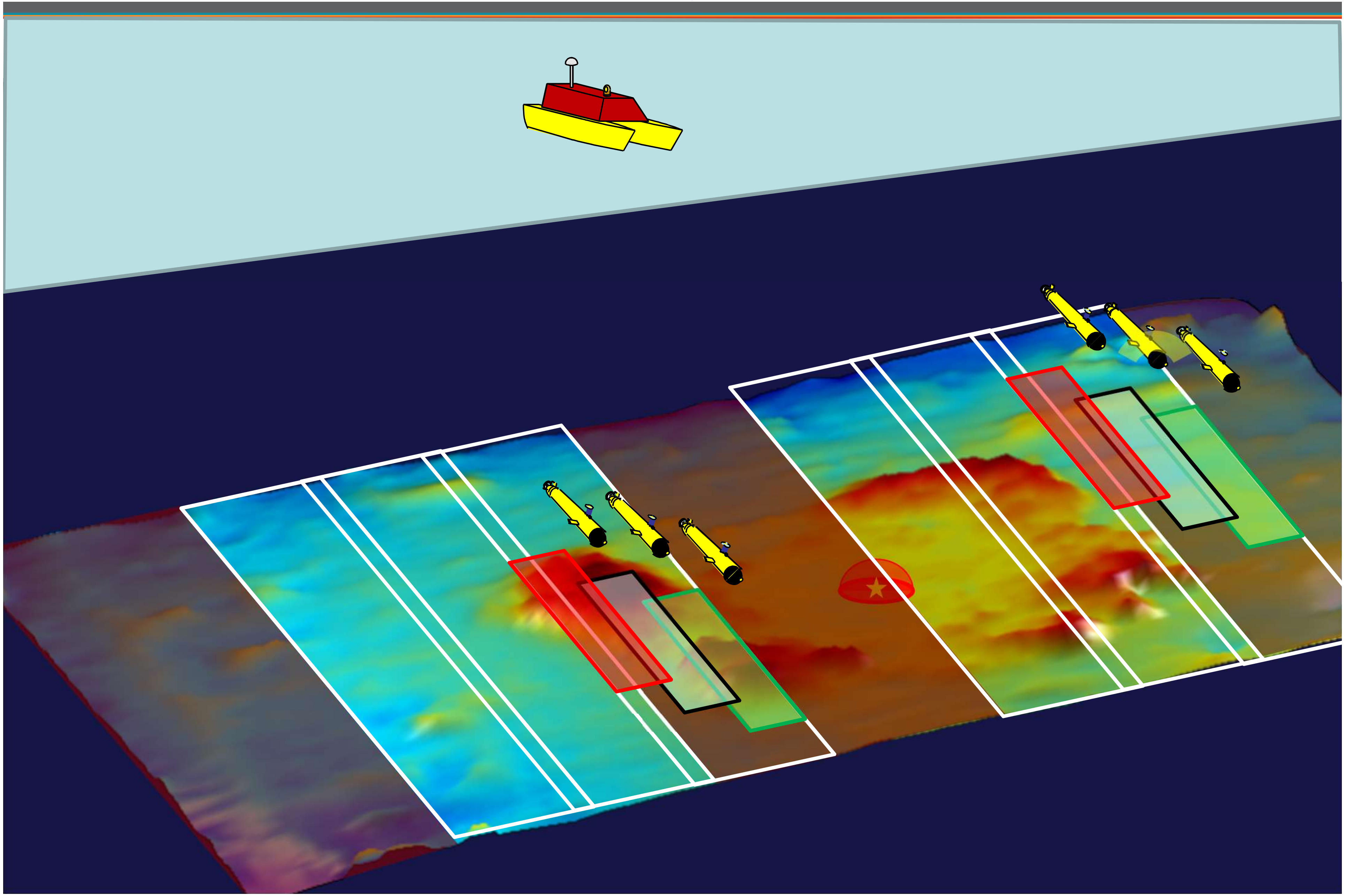
Supervisors: Mcf. Lionel Lapierre
Prof. Bruno Jouvencel

24/02/2011, Montpellier

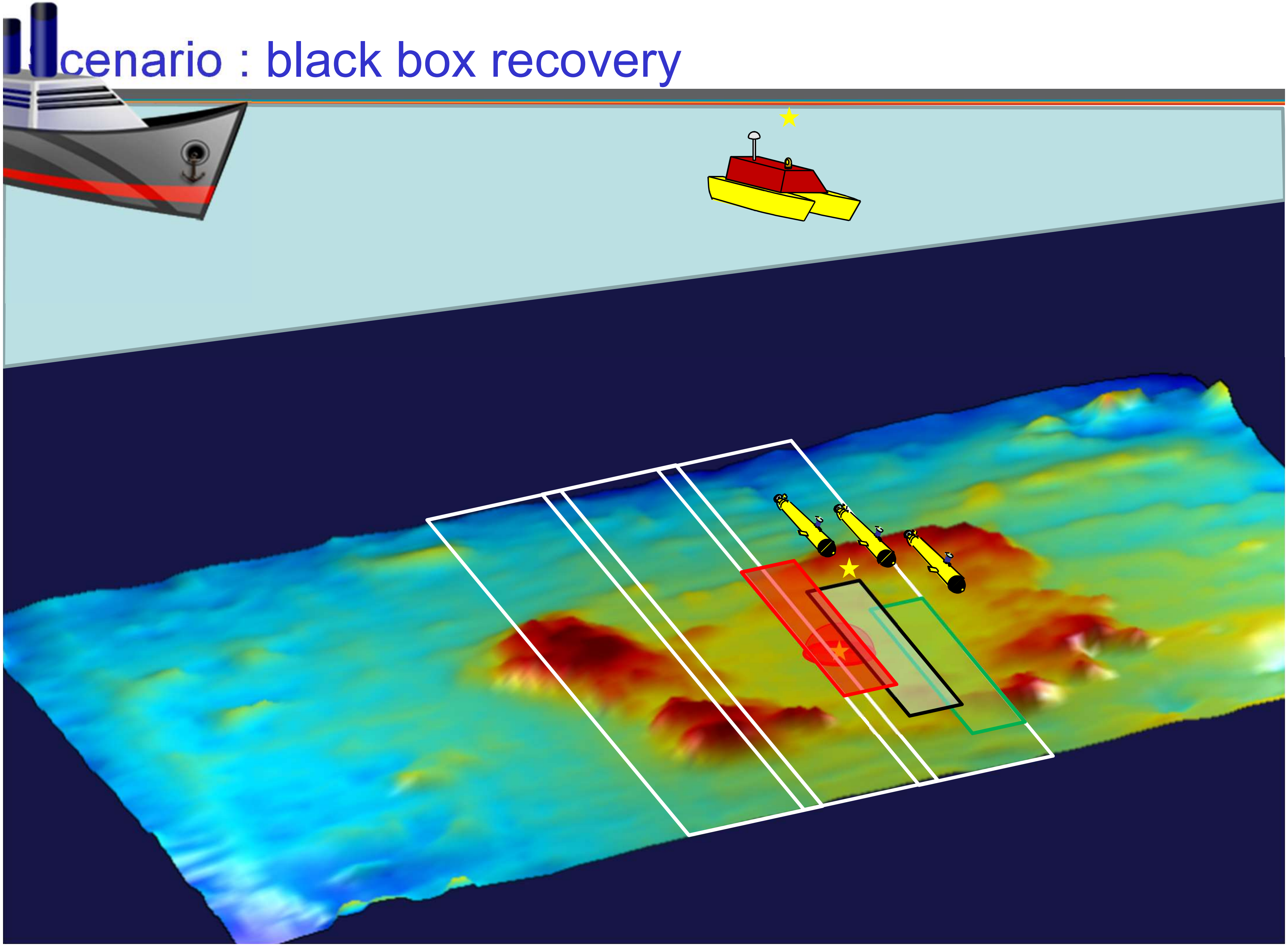
Scenario : black box recovery



Scenario : black box recovery



Scenario : black box recovery



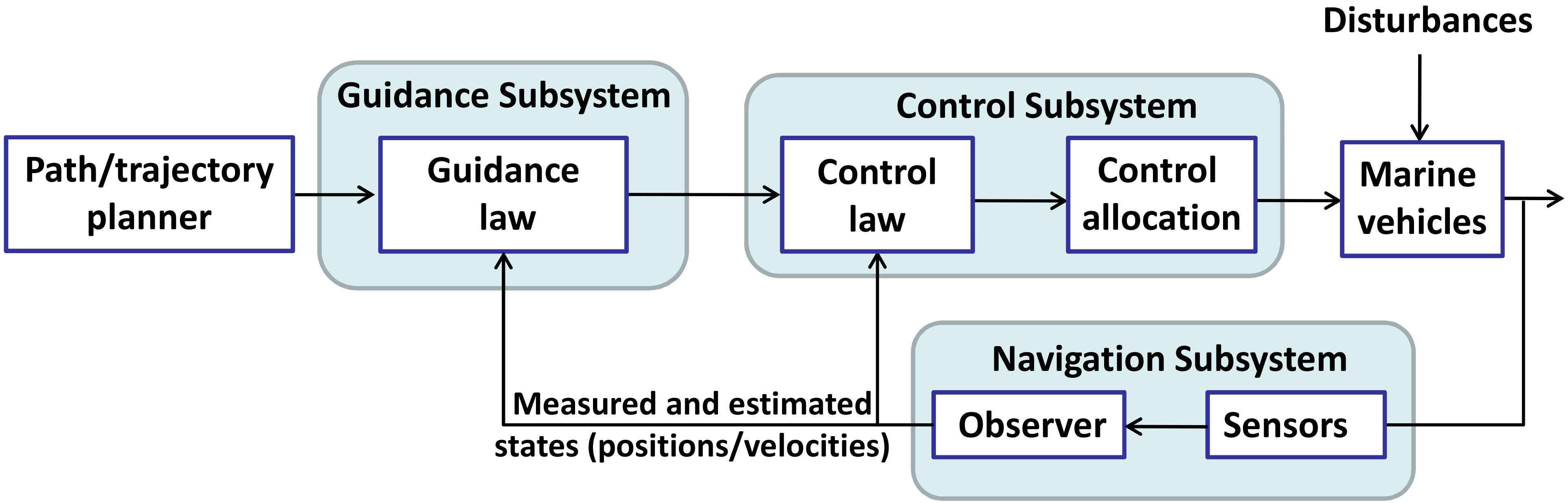
Background

Key issues

- Autonomous vehicles
- Underactuation / Isoactuation
- Constrained communication
- Coordinated path-following
- Formation keeping and RDVs
- Centralized / decentralized control

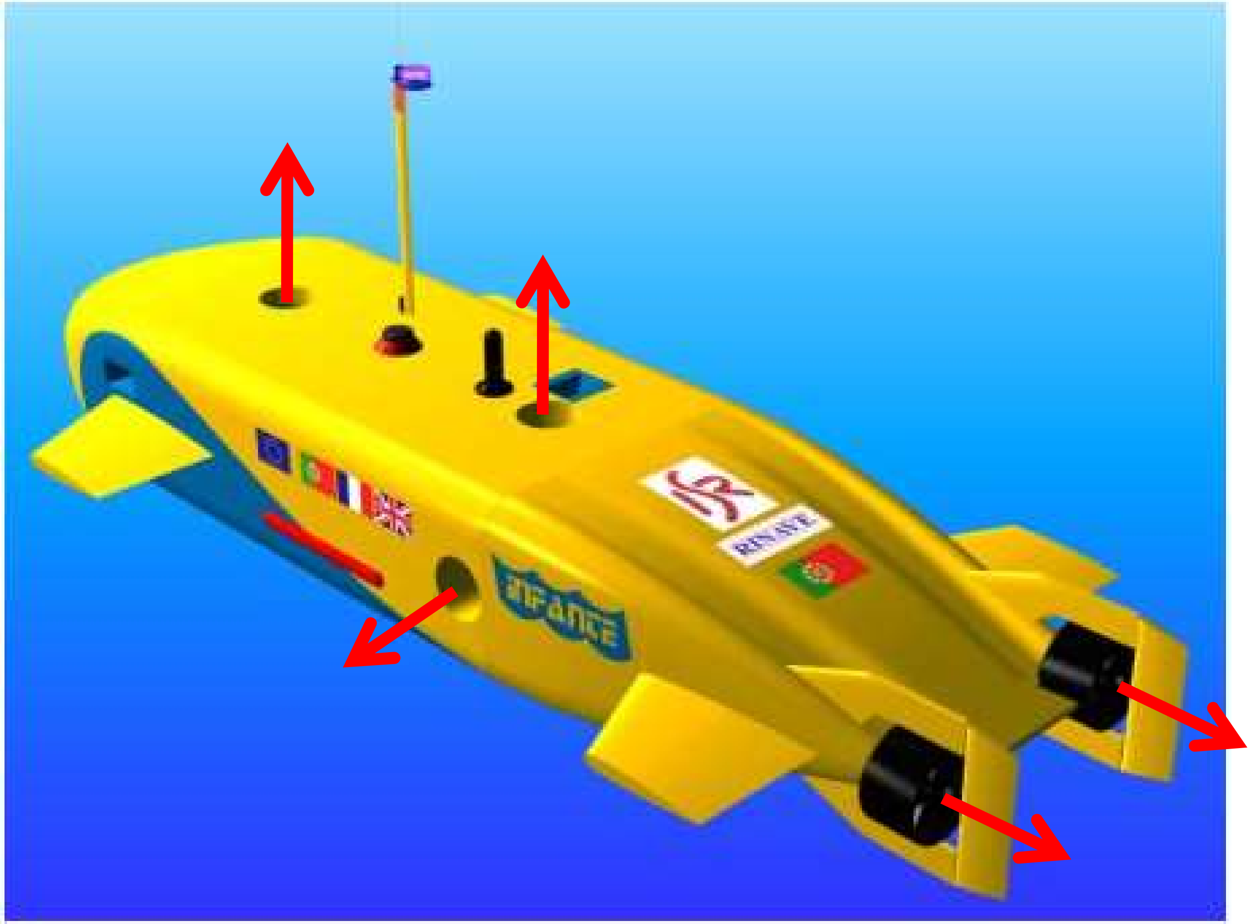
Background

Closed-loop marine control system



Motivation

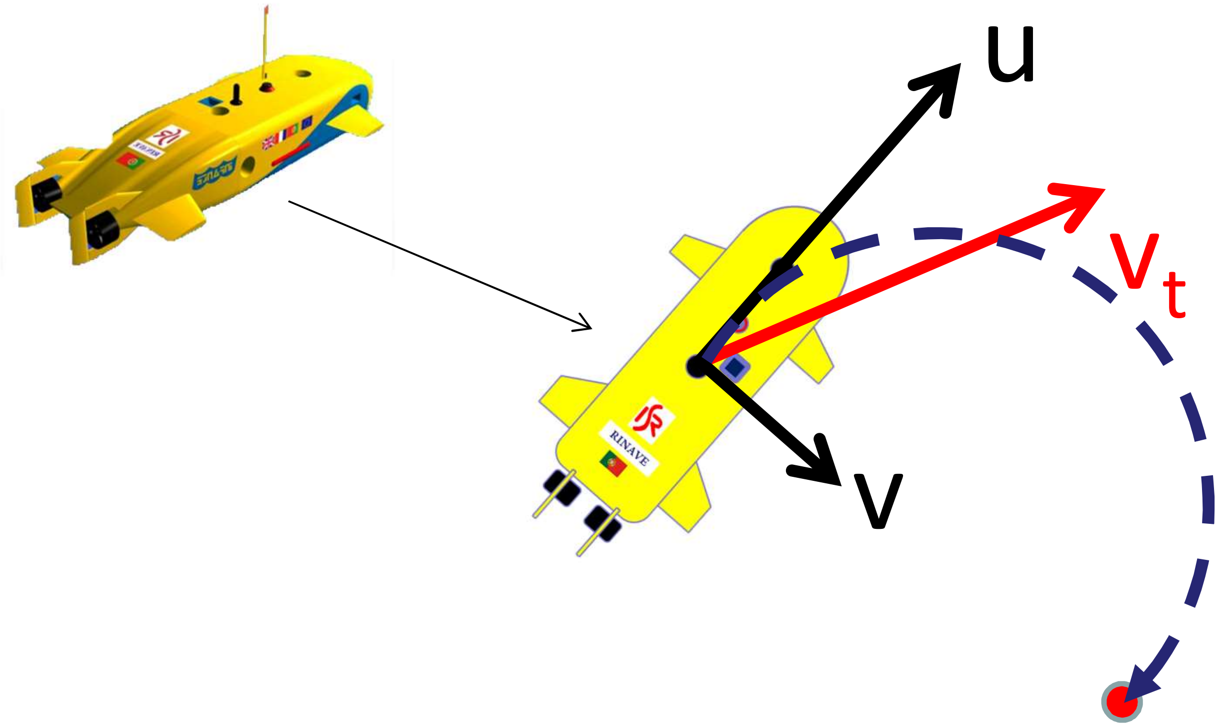
Why Autonomous underactuacted vehicle



Motivation

Motion control of underactuated vehicles

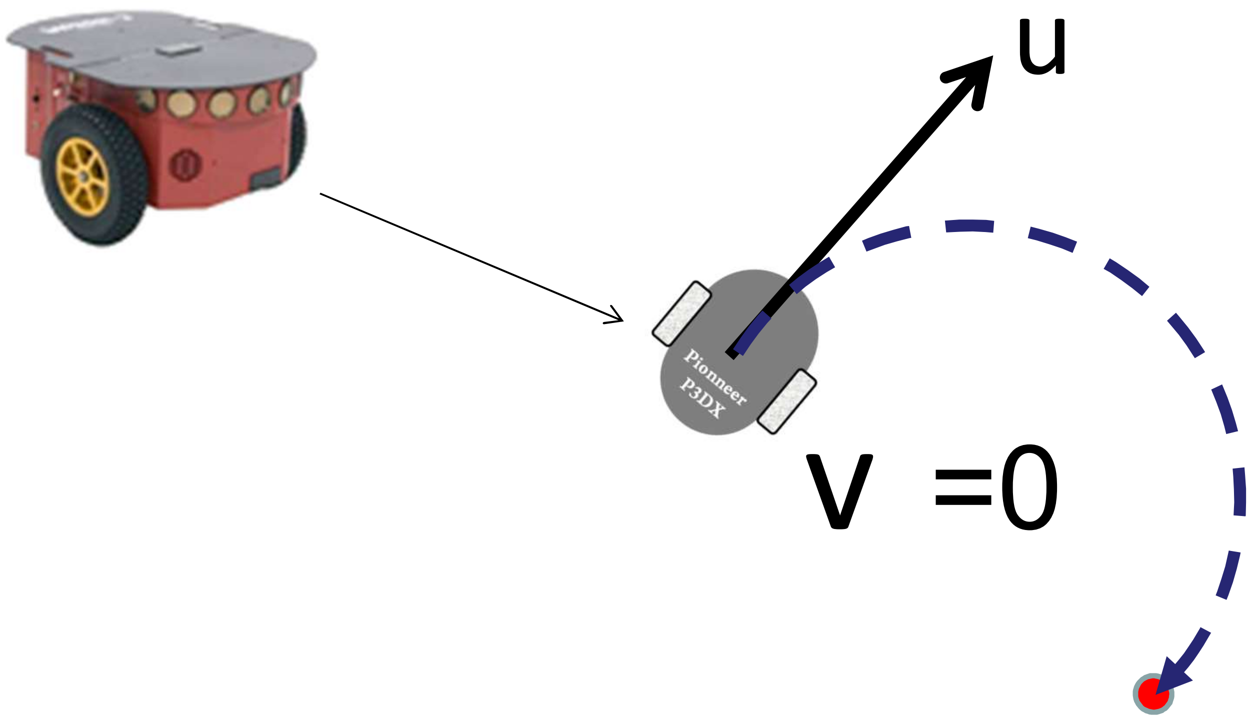
Side-slip ($v \neq 0$) , but no sway actuator



Motivation

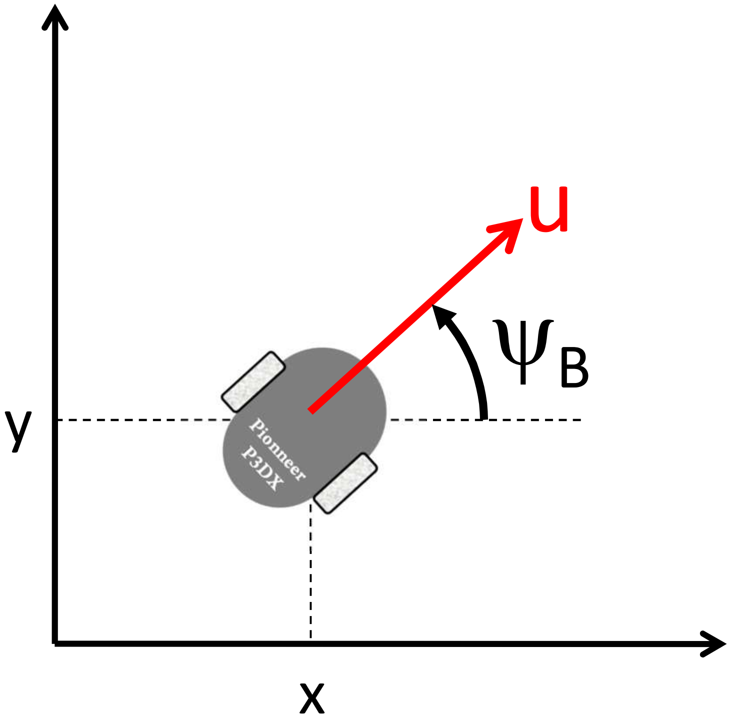
Motion control of unicycle wheeled system

No side-slip ($\mathbf{v}$ =0)

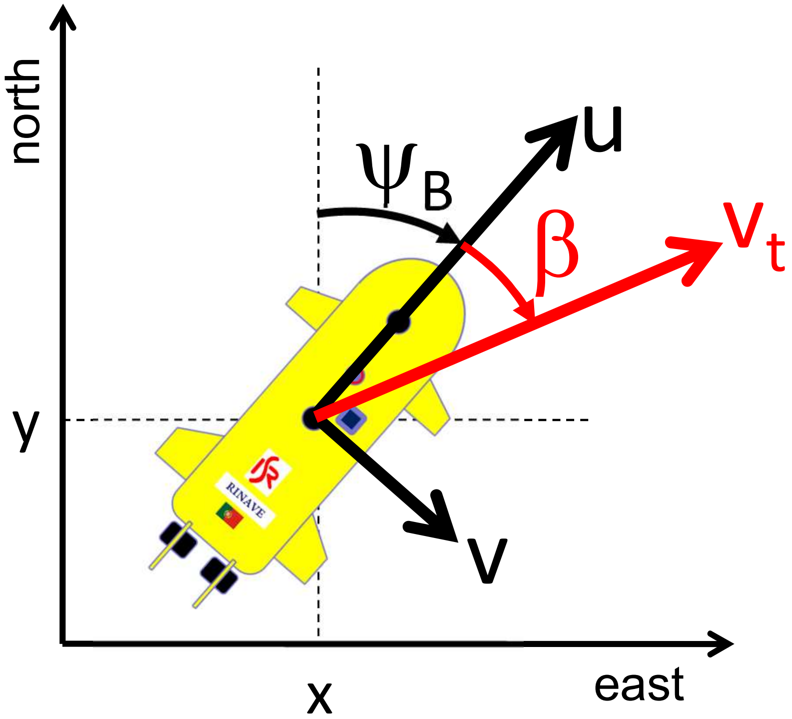


Modeling

Unicycle V.S. AUV



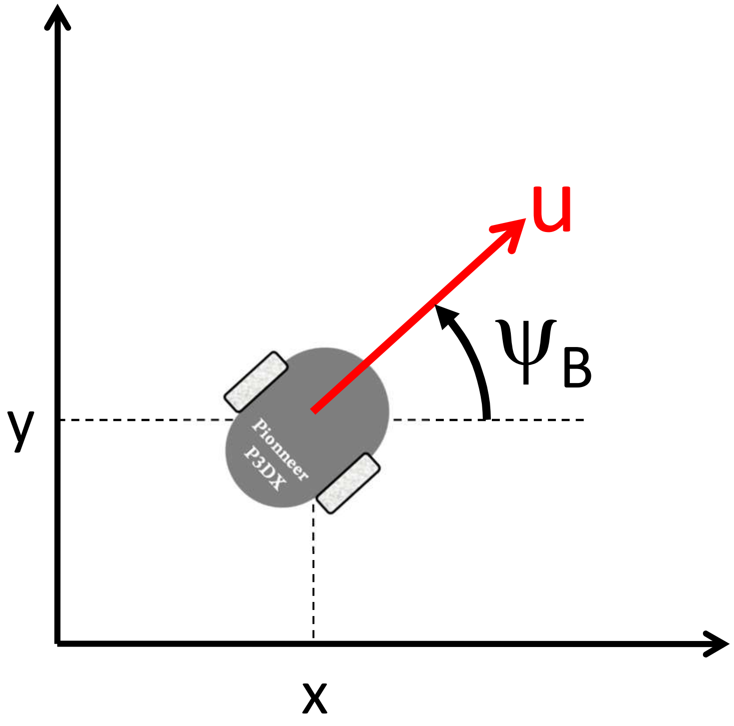
$$\left\{\begin{array}{l} \dot{x} = ucos\psi_B \\ \dot{y} = usin\psi_B \\ \dot{\psi}_B = r \end{array}\right.$$



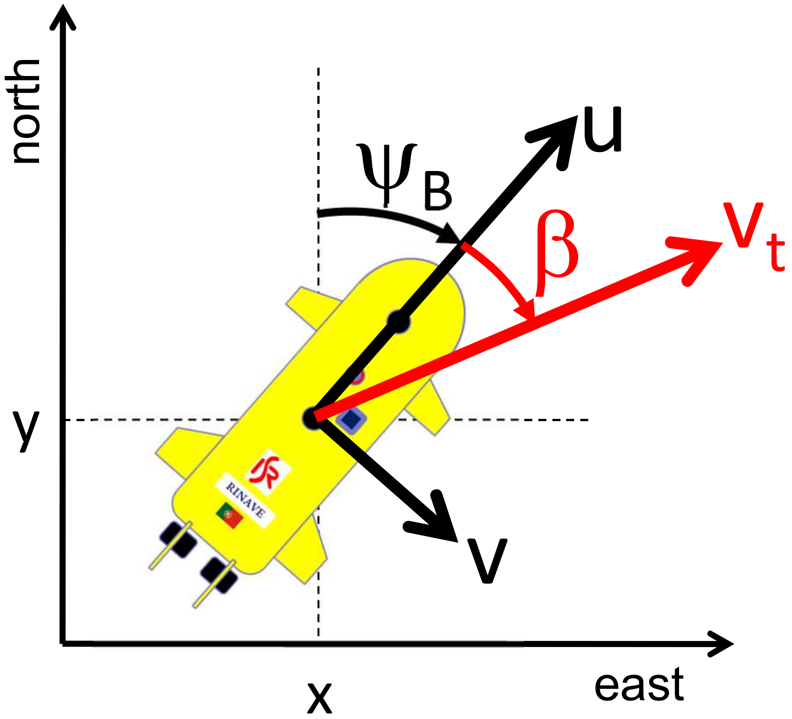
$$\left\{\begin{array}{l} \dot{x} \\ \dot{y} \\ \dot{\psi} \end{array}\right. \left\{\begin{array}{ll} \dot{x} = v_t \cos\psi & \psi_B \\ \dot{y} = v_t \sin\psi & \psi_B \\ \dot{\psi} = r + \dot{\beta} & \end{array}\right.$$

Modeling

Unicycle V.S. AUV



$$\dot{y}\cos\psi_B - \dot{x}\sin\psi_B = 0$$

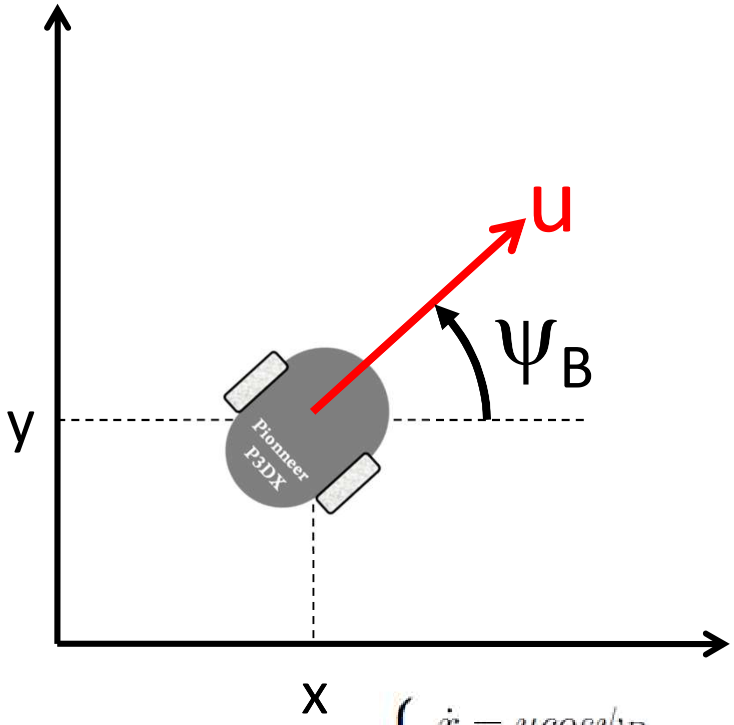


$$\begin{aligned} m_{22}\dot{v} + m_{23}\dot{r} + m_{11}ur \\ + d_{22}v + d_{23}r = 0 \end{aligned}$$

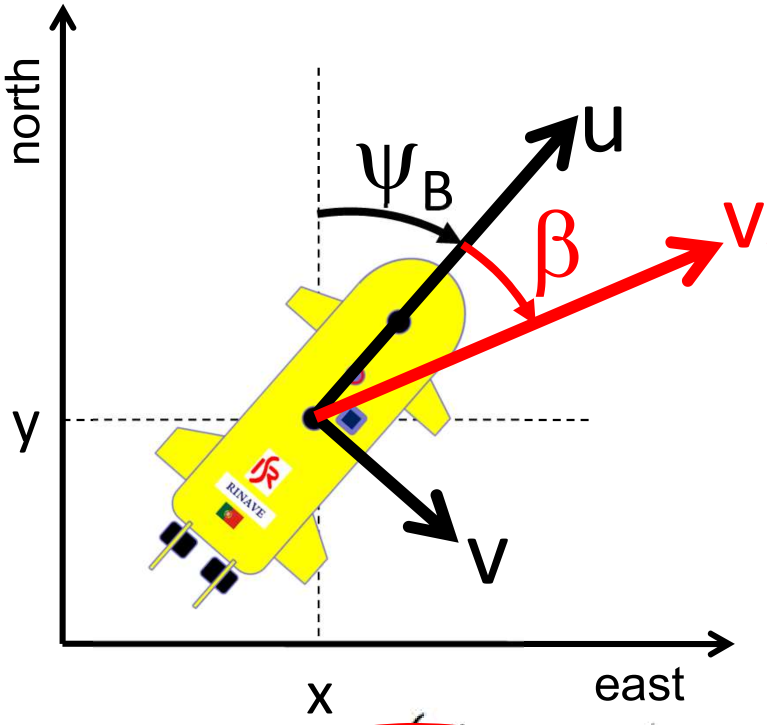
Nonholonomic constraints (1st and 2nd order)

Modeling

Unicycle V.S. AUV



$$\beta = 0, \forall t \quad \begin{cases} \dot{x} = u cos\psi_B \\ \dot{y} = u sin\psi_B \\ \dot{\psi}_B = r \end{cases}$$



$$\dot{\beta} = \frac{u\boxed{\dot{u}} - v\boxed{\dot{v}}}{v_t^2} \quad \begin{cases} \dot{x} = v_t \cos\psi \\ \dot{y} = v_t \sin\psi \\ \dot{\psi} = r + \boxed{\dot{\beta}} \end{cases}$$

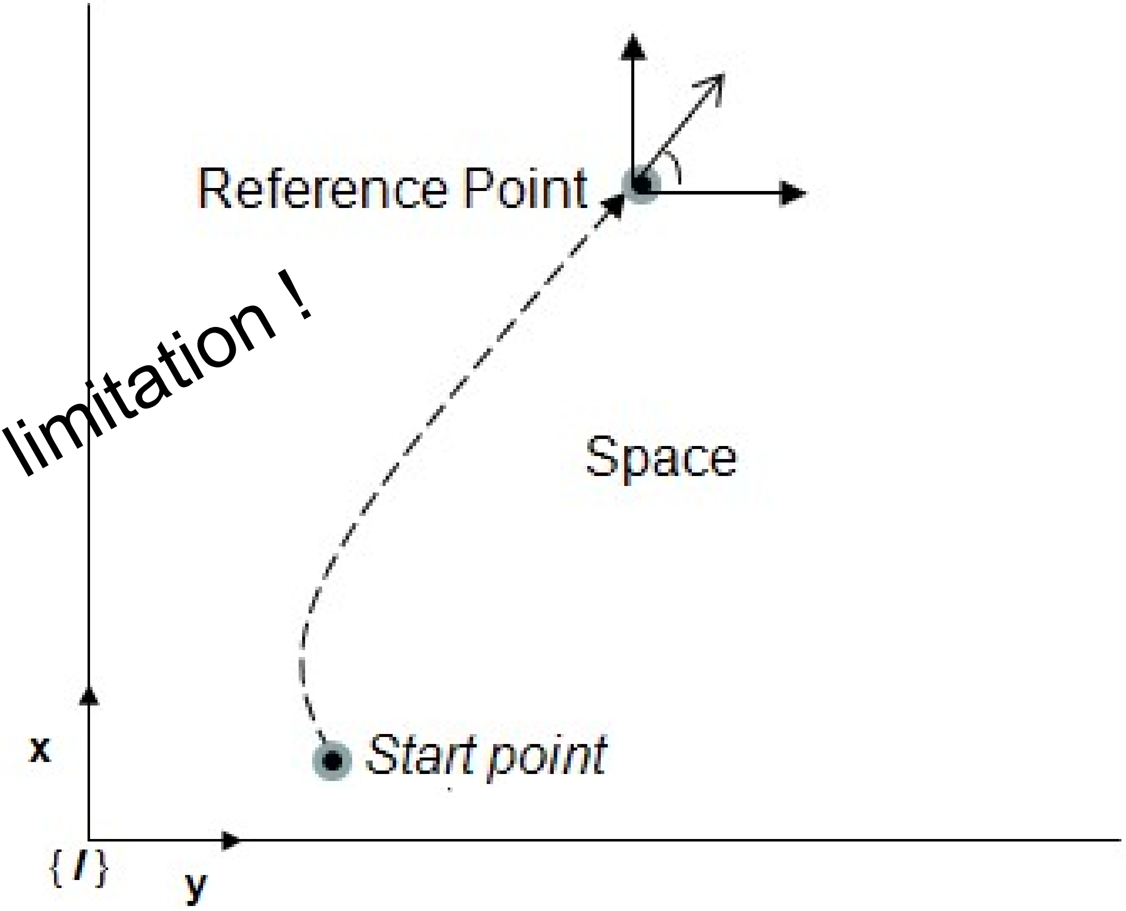
Kinematic Control

Dynamic Control

Motion Control

Current motion control strategies

Point Stabilisation (PS)

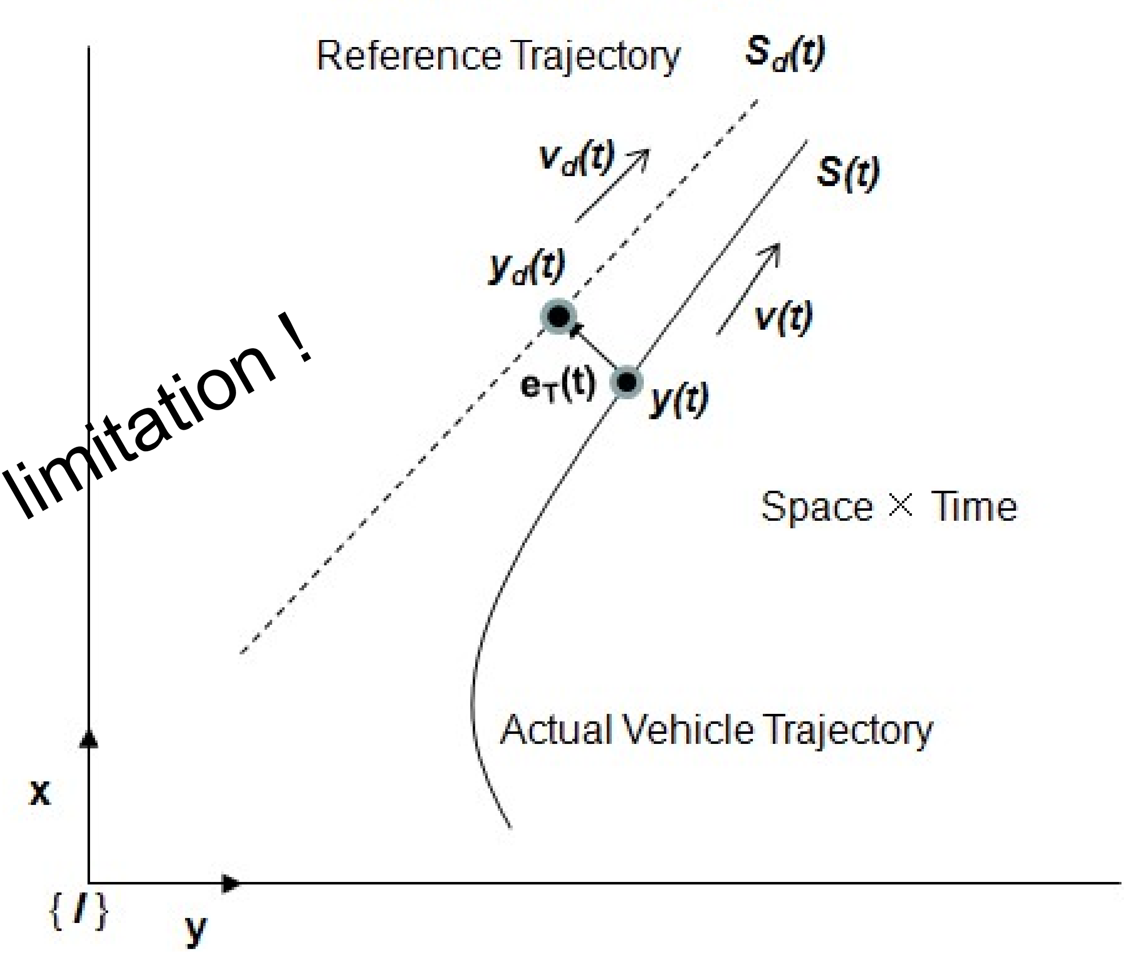


Brocket's limitation !

Motion Control

Current motion control strategies

Trajectory Tracking (TT)

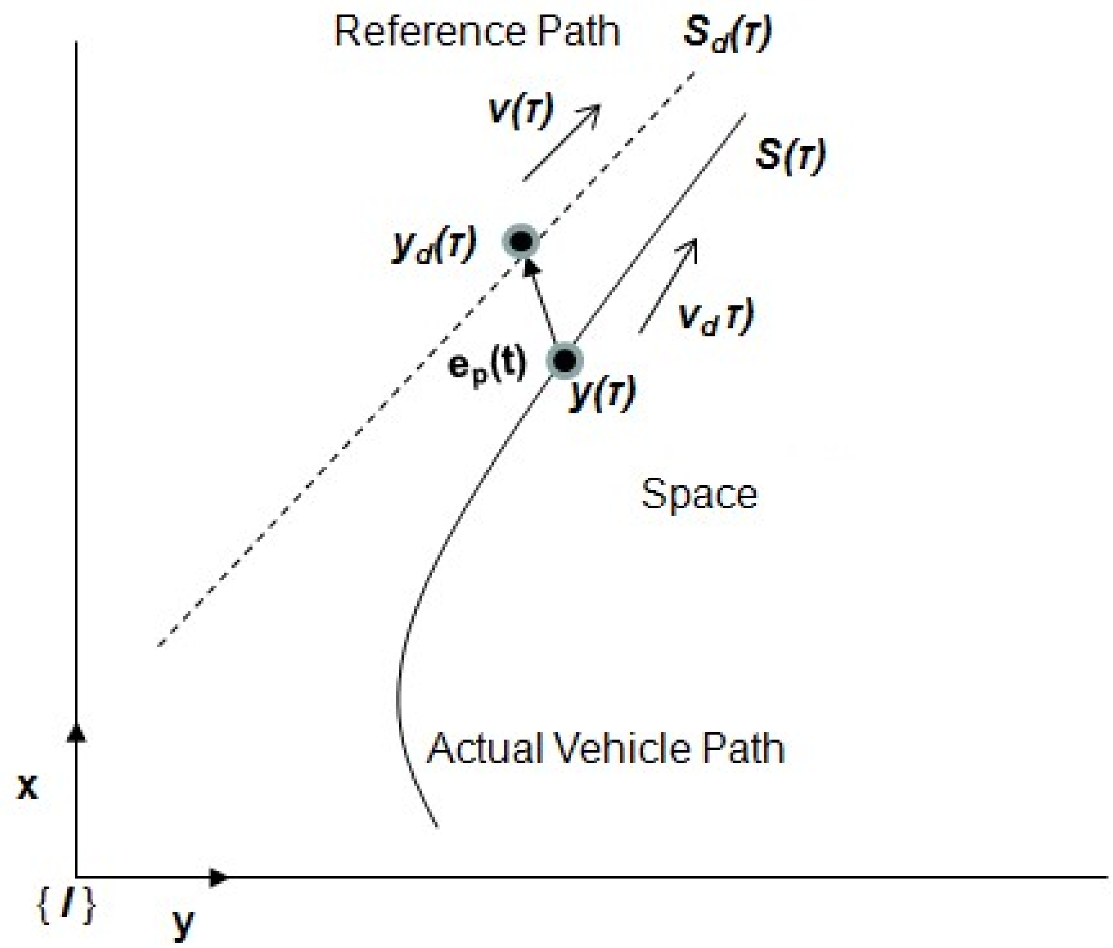


Brocket’s limitation !

Motion Control

Current motion control strategies

Path Following (PF)



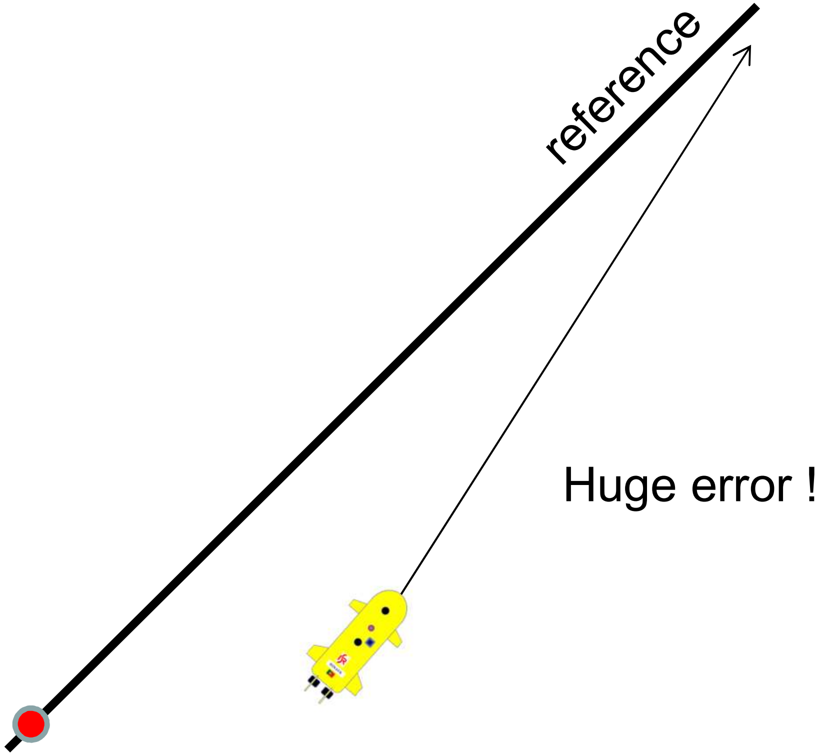
Motion Control

Trajectory Tracking VS. Path Following

Trajectory Tracking (TT)

- Time dependant reference

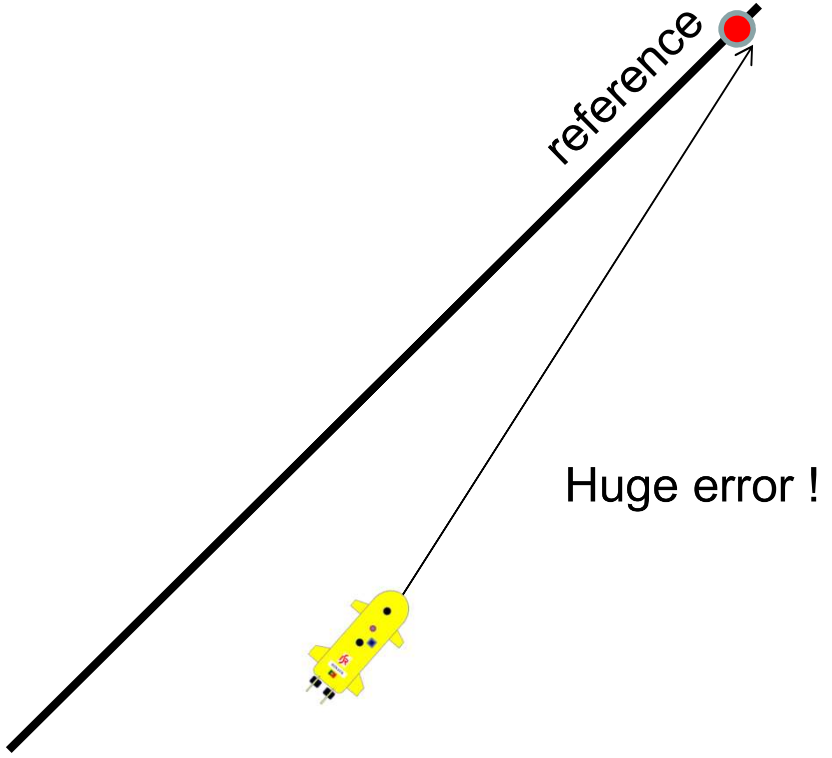
(The target flies with time, no matter the current situation of the vehicle)



Trajectory Tracking VS. Path Following

Trajectory Tracking (TT)

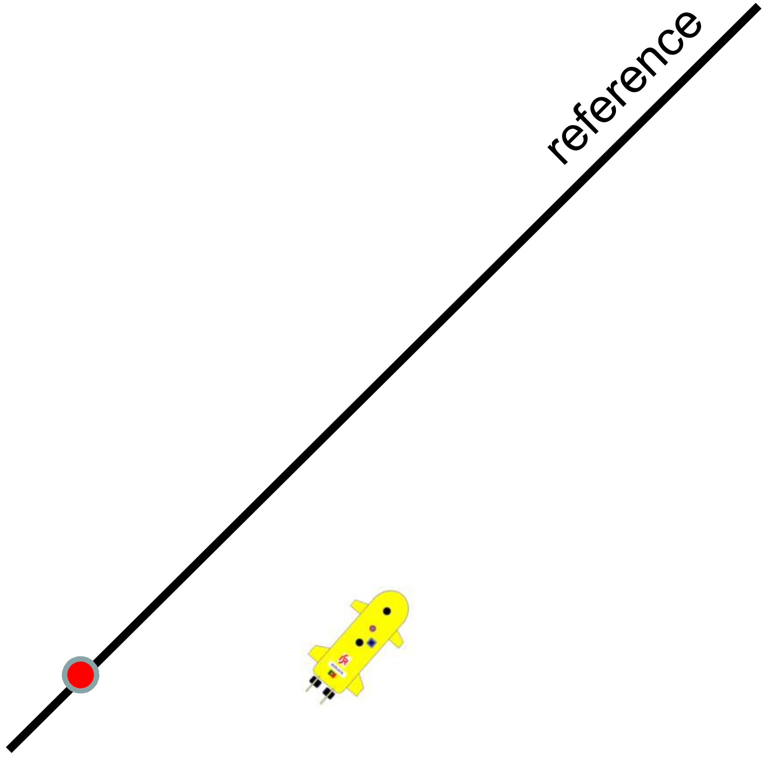
- Time dependant reference
(The target flies with time, no matter the current situation of the vehicle)
- Actuators are easily pushed to saturation



Motion Control

Trajectory Tracking VS. Path Following

Trajectory Tracking (TT)



- Time dependant reference

(The target flies with time, no matter the current situation of the vehicle)

- Actuators are easily pushed to saturation
- Aggressive maneuvers

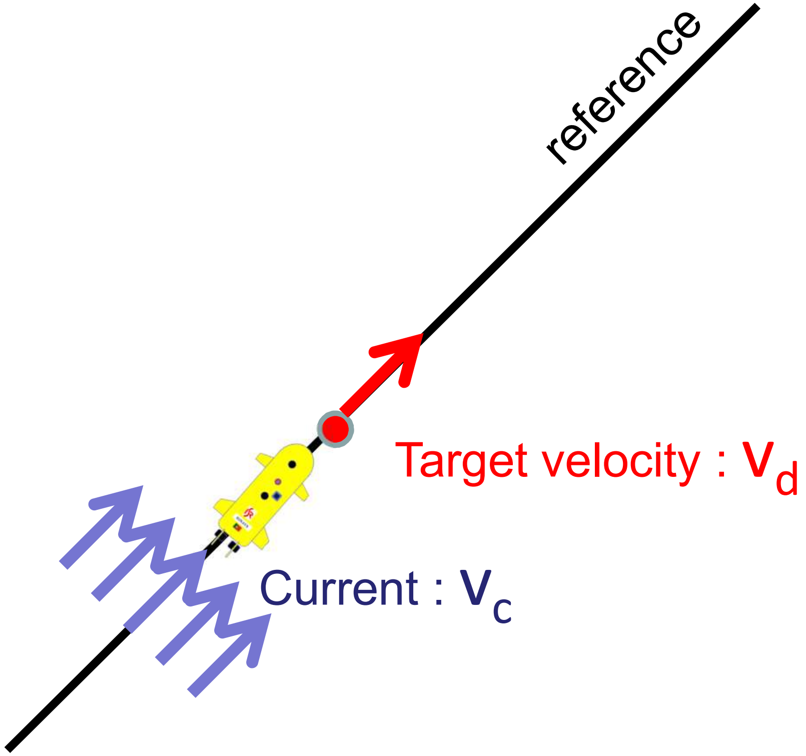
(The vehicle may turn back in its attempt to be at a specific point at a prescribed time)

Motion Control

Trajectory Tracking VS. Path Following

Trajectory Tracking (TT)

- Time dependant reference
  (The target flies with time, no matter the current situation of the vehicle)
- Actuators are easily pushed to saturation
- Aggressive maneuvers
  (The vehicle may turn back in its attempt to be at a specific point at a prescribed time)
- Risk of Stalling
  (loosing efficiency of the surfaces of control)

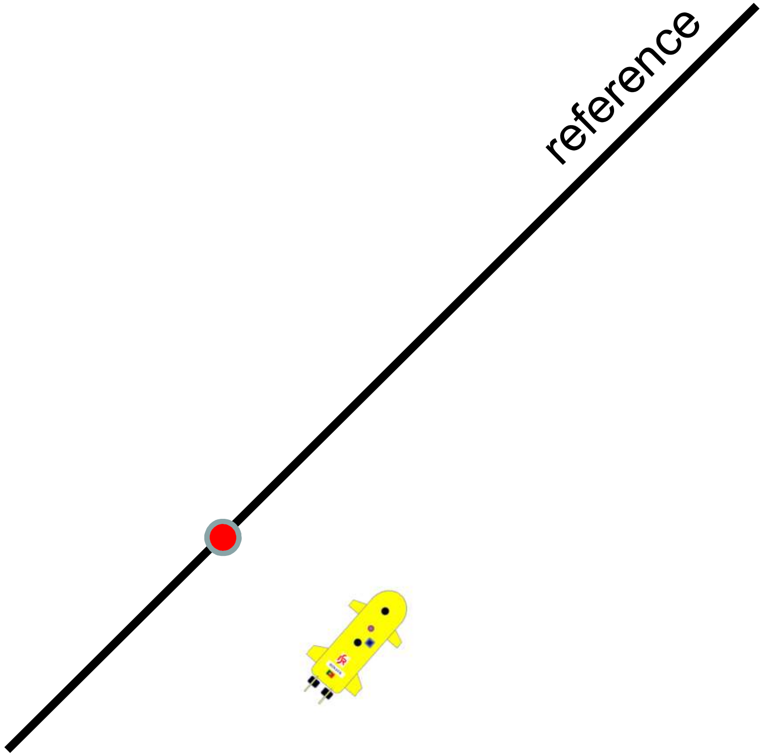


AUV Vel/water = $V_d - V_c = 0$!

Motion Control

Trajectory Tracking VS. Path Following

Path Following (PF)

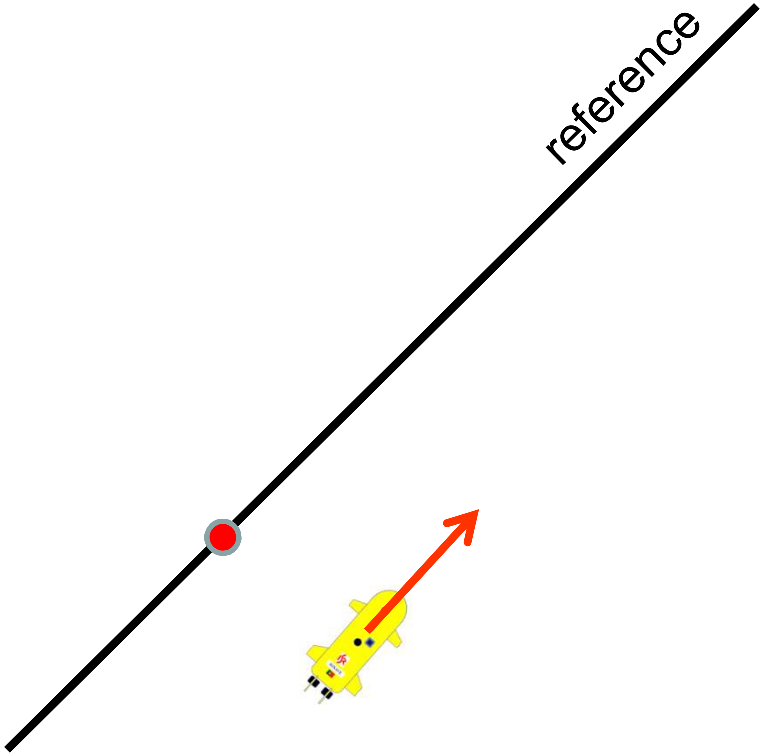


- Time free reference
(closest point)

Trajectory Tracking VS. Path Following

Path Following (PF)

- Time free reference
(closest point)
- Decoupled control u / r
(u arbitrarily chosen)

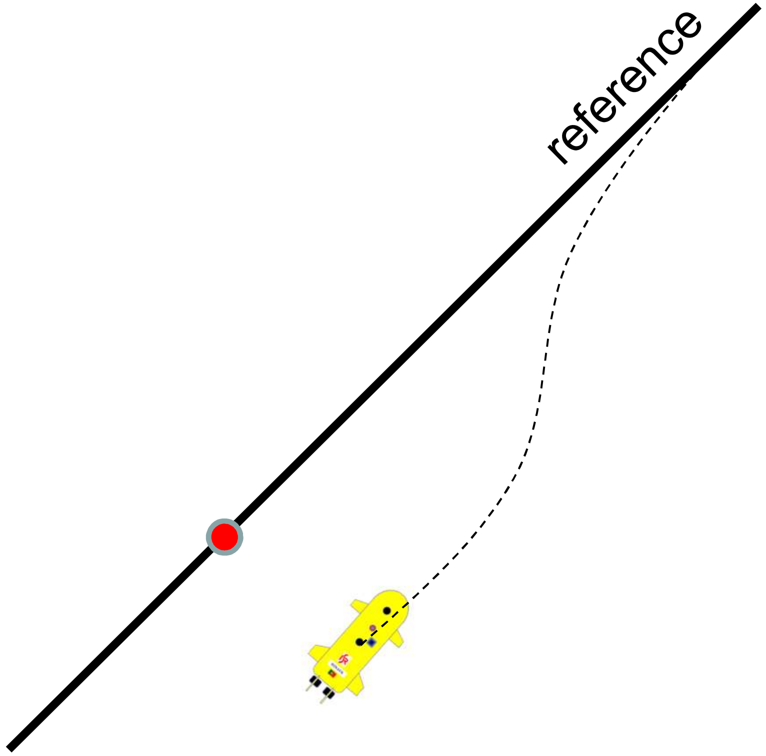


Motion Control

Trajectory Tracking VS. Path Following

Path Following (PF)

- Time free reference
  (closest point)
- Decoupled control u / r
  (u arbitrarily chosen)
- Smoother convergence

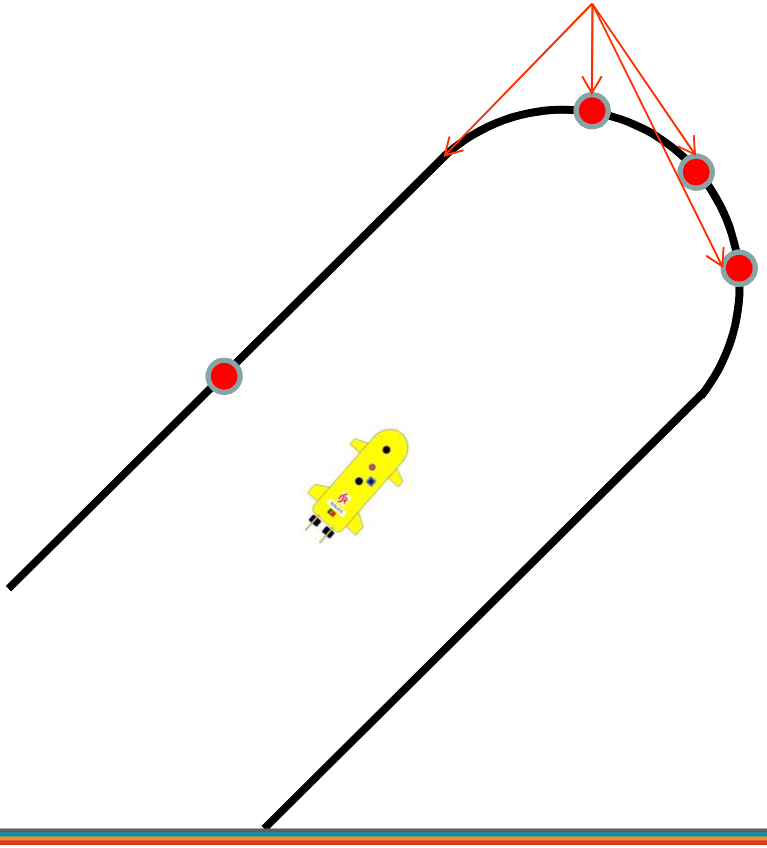


Motion Control

Trajectory Tracking VS. Path Following

Path Following (PF)

- Time free reference
(closest point)
- Decoupled control u / r
(u arbitrarily chosen)
- Smoother convergence
- r is driven w.r.t a guidance strategy
- Non singular virtual target principle



The closest point is no more unique !

Trajectory Tracking VS. Path Following

Path Following (PF)

- Time free reference

(closest point)

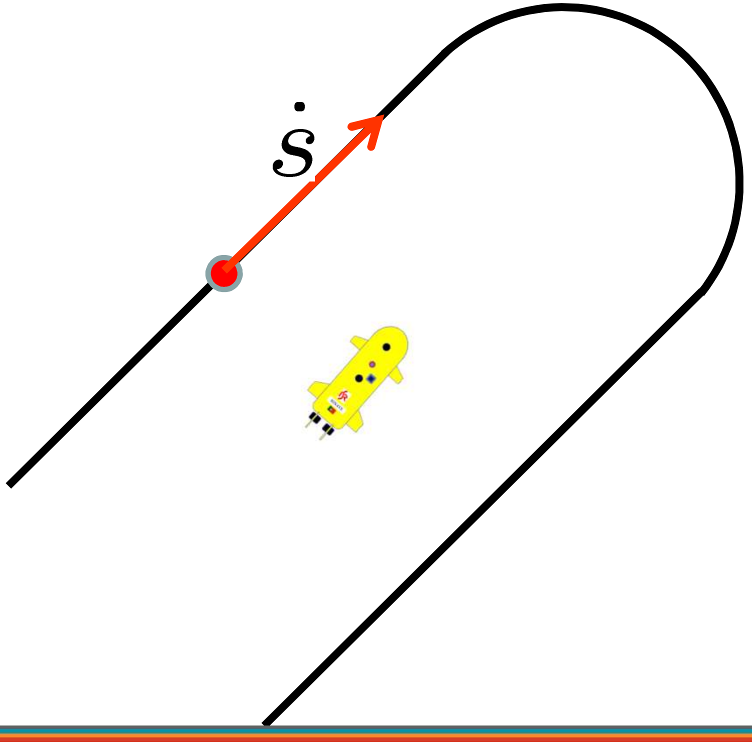
- Decoupled control u / r

(u arbitrarily chosen)

- Smoother convergence
- r is driven w.r.t a guidance strategy
- Non singular virtual target principle

Virtual Target Principle :

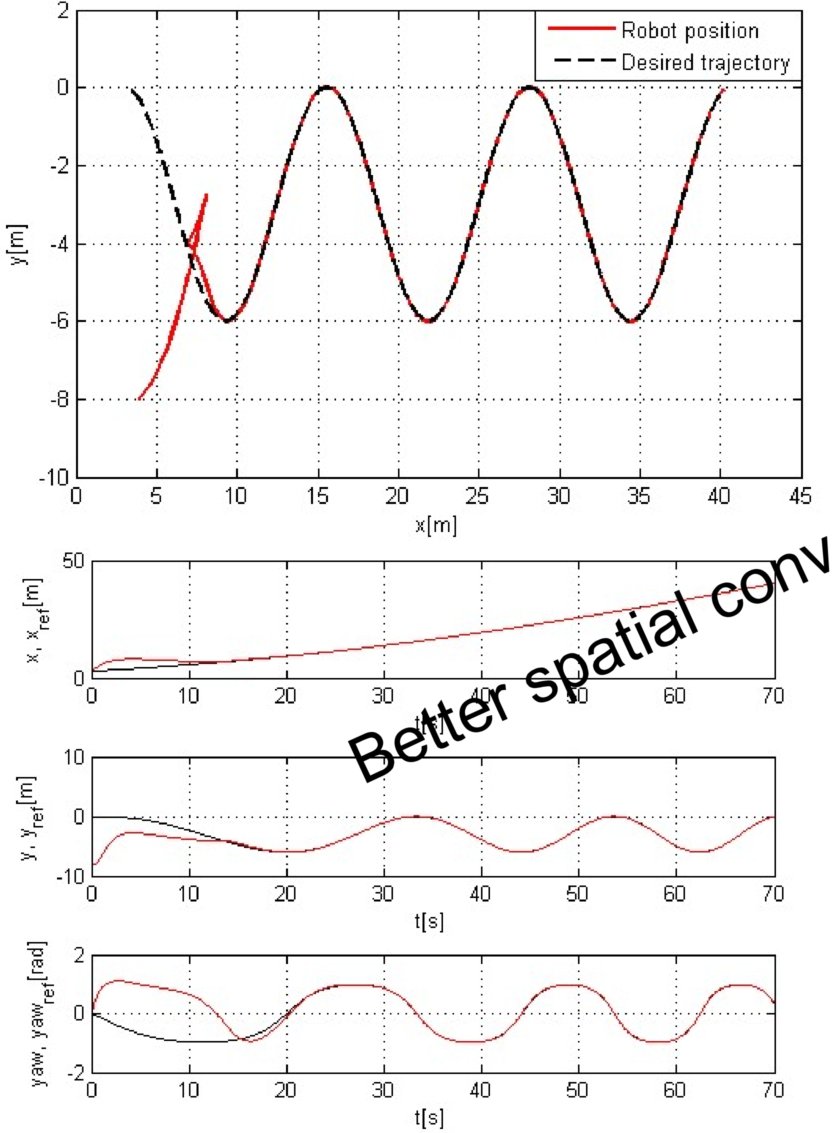
$$\dot{s} = v_t \cos\theta + K_s s_1$$



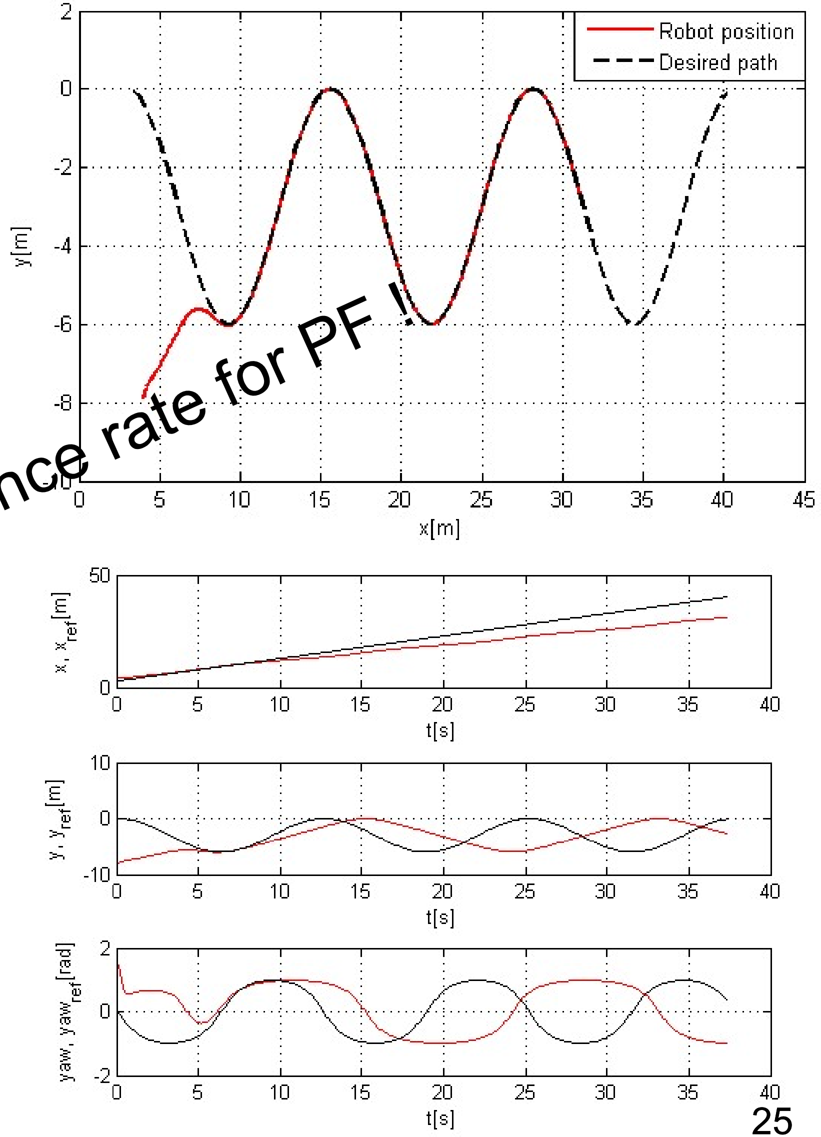
Motion Control

Trajectory Tracking V.S. Path Following

Trajectory Tracking (TT)



Path Following (PF)



Better spatial convergence rate for PF !

Motion Control

Trajectory Tracking VS. Path Following

Path Following (PF)

- Time free reference
- Decoupled control u / r
- Smoother convergence
- r is driven w.r.t a guidance strategy
- Non singular virtual target principle

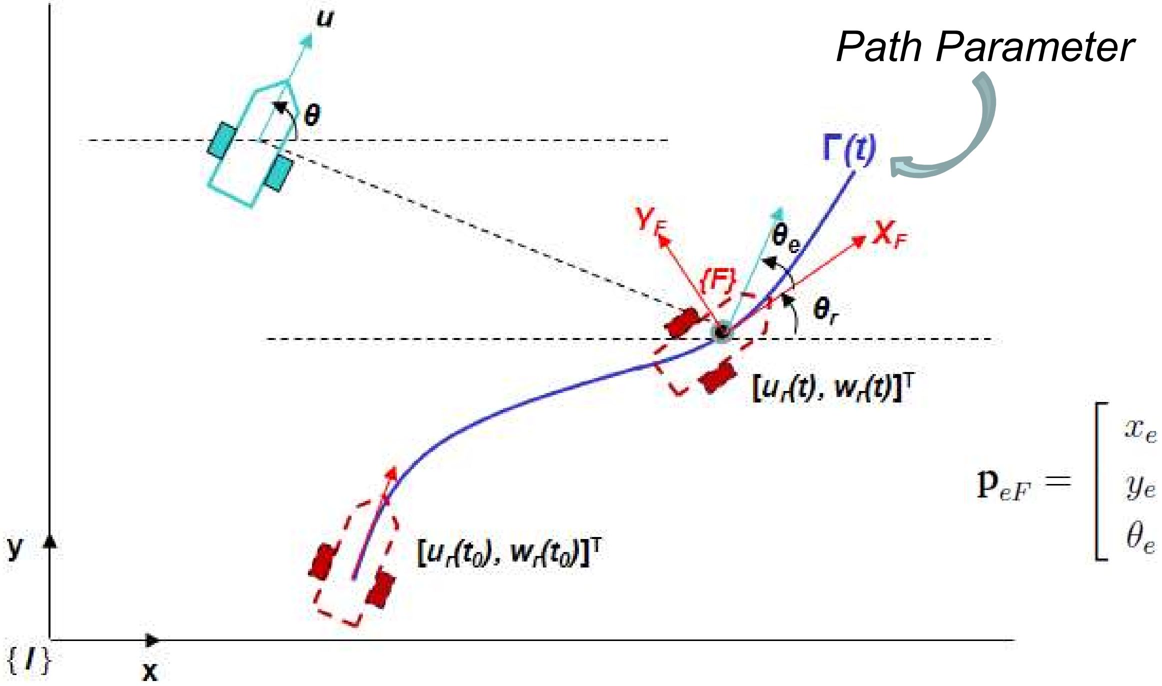
Trajectory Tracking (TT)

- Time dependant reference
- Actuators are easily pushed to saturation
- Aggressive maneuvers
- Risk of Stalling
- Better Convergence rate

Control Design

Mathematical framework: unicycle

Trajectory Tracking (TT)



Control Objective

$$\lim_{t\to\infty} \|\mathbf{p}_{eF}\| = 0$$

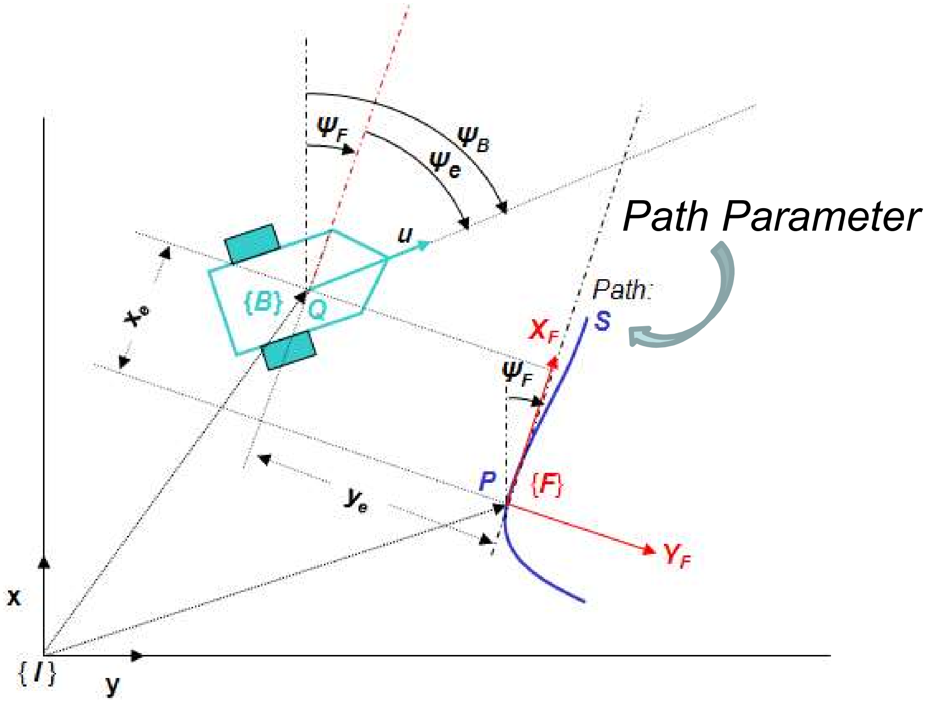
$$\mathbf{p}_{eF} = \begin{bmatrix} x_e \\ y_e \\ \theta_e \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r & 0 \\ -\sin\theta_r & \cos\theta_r & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x - x_r \\ y - y_r \\ \theta - \theta_r \end{bmatrix}$$

$$V = \frac{1}{2}(x_e^2 + y_e^2 + \theta_e^2) \Longrightarrow \begin{bmatrix} u \\ \omega \end{bmatrix} = \begin{bmatrix} u_r \cos\theta_e - k_1 x_e \cos\theta_e - k_1 y_e \sin\theta_e \\ \omega_r + u_r\left(x_e \frac{\sin\theta_e}{\theta_e} \sin\theta_e - y_e \frac{\sin\theta_e}{\theta_e} \cos\theta_e\right) - k_2\theta_e \end{bmatrix}$$

Control Design

Mathematical framework: unicycle

Path Following (PF)



Control Objective

$$\lim_{t\to\infty} \|P_{eF}\| = 0$$

$$\lim_{t\to\infty} |u(t) - u_d(t)| = 0$$

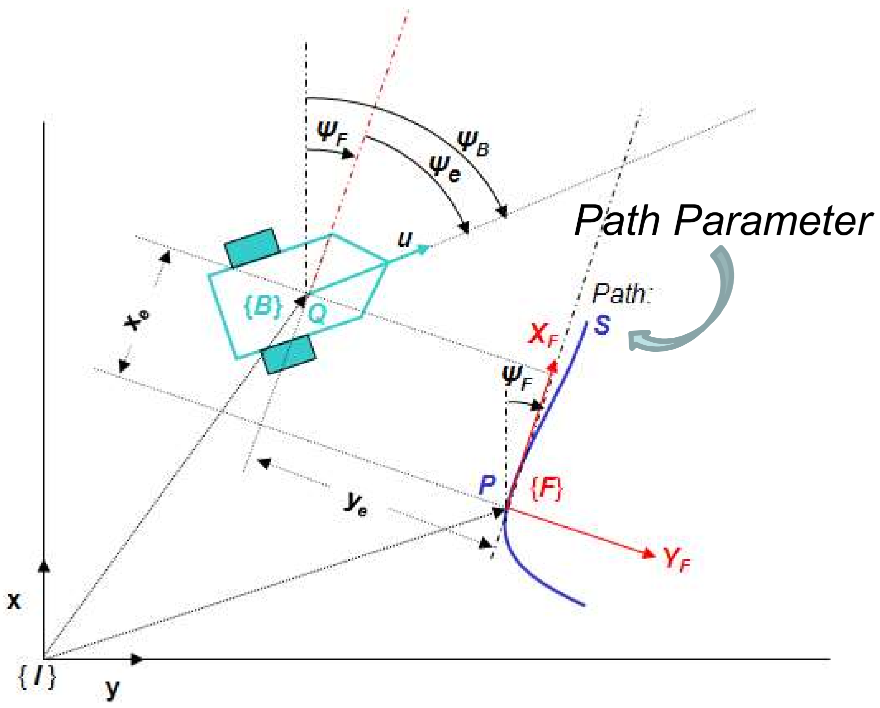
$$\begin{bmatrix} \dot{x}_e \\ \dot{y}_e \\ \dot{\psi}_e \end{bmatrix} = \begin{bmatrix} c_c(s)\dot{s}y_e - \dot{s} + u\cos\psi_e \\ -c_c(s)\dot{s}x_e + u\sin\psi_e \\ \omega - c_c(s)\dot{s} \end{bmatrix}$$

$$V_1 = \frac{1}{2}[x_e^2 + y_e^2 + (\psi_e - \psi_{los})^2] \Longrightarrow \begin{bmatrix} \alpha_u \\ \alpha_r \\ \dot{s} \end{bmatrix} = \begin{bmatrix} u_d \\ c_c\dot{s} + \dot{\delta} - k_\theta(\psi_e - \delta) \\ u_d\cos\psi_e + k_x x_e \end{bmatrix}$$

Control Design

Mathematical framework: unicycle

Path Following (PF)



Path Parameter

Backstepping dynamics

$$M = \begin{pmatrix} m & 0 \\ 0 & I \end{pmatrix}$$

Virtual control inputs

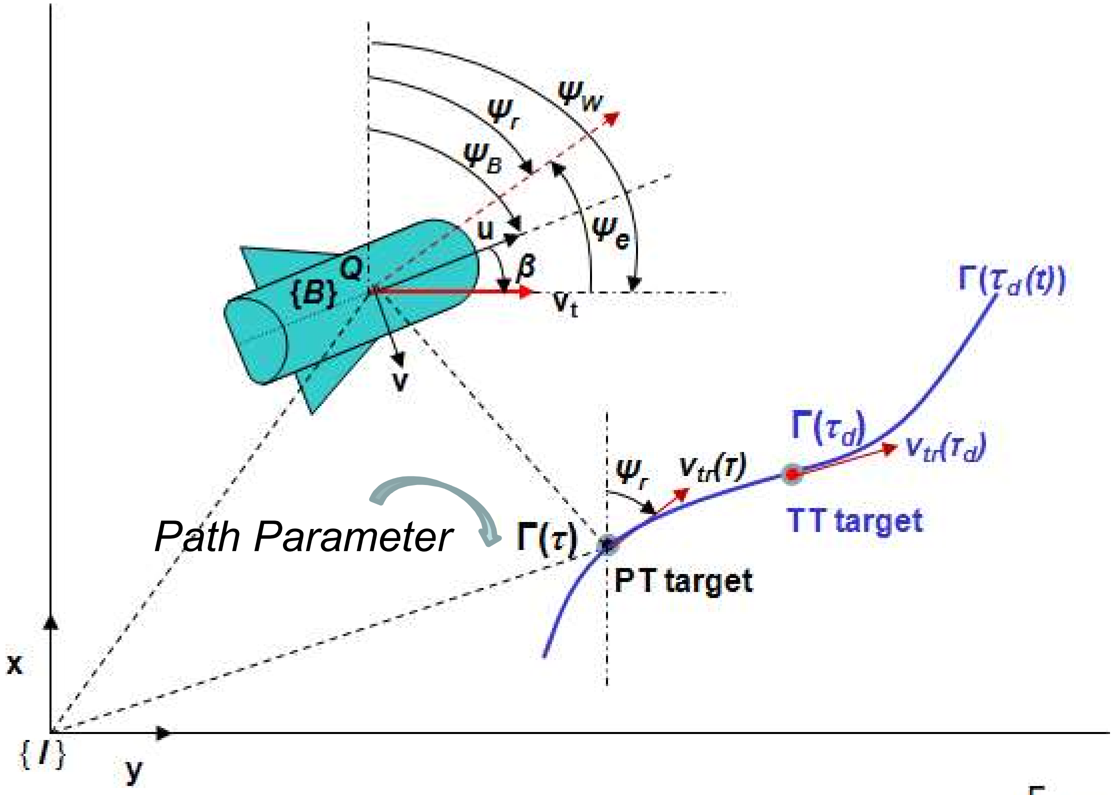
$$z = \begin{pmatrix} z_u \\ z_r \end{pmatrix} = \begin{pmatrix} u - \alpha_u \\ r - \alpha_r \end{pmatrix}$$

$$V_{dyn} = V_{kin} + \frac{1}{2} z^T M z \quad \Rightarrow \quad \begin{cases} F = m\dot{u} = m\dot{\alpha}_u - k_3 z_u = m\dot{u}_d - k_3(u - u_d) \\ N = I\dot{r} = I\dot{\alpha}_r - (\psi_e - \delta) - k_4 z_r \end{cases}$$

Control Design

Mathematical framework: AUV

Path Tracking (PT)



Objectives

1) Geometric assignment

$$\lim_{t\to\infty} \|\mathbf{p}_{eB}\| = 0$$

2) Temporal assignment

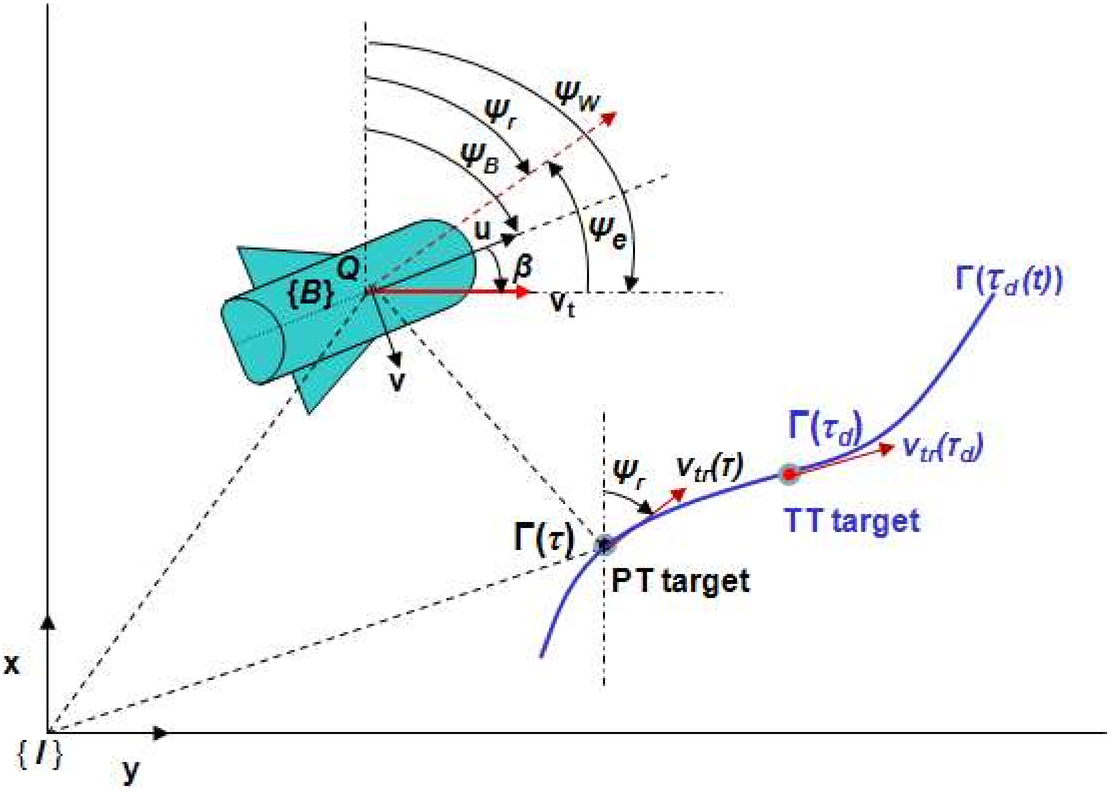
$$\lim_{t\to\infty} |\tau(t) - \tau_d(t)| = 0$$

$$V = (1-\lambda)\frac{(x_e^2 + y_e^2 + \frac{1}{\gamma}\psi_e^2)}{2} + \lambda\frac{k_\tau(\tau-\tau_d)^2}{2} \Rightarrow \begin{bmatrix} v_t \\ \omega \\ \dot{\tau} \end{bmatrix} = \begin{bmatrix} k_x x_e + \bar{v}_{tr}\dot{\tau}_d\cos\psi_e \\ \bar{\omega}_r\dot{\tau}_d - \dot{\beta} + \gamma y_e \bar{v}_{tr}\dot{\tau}_d\frac{\sin\psi_e}{\psi_e} + k_\psi\psi_e \\ \dot{\tau}_d - k_v\tanh\Phi_e \end{bmatrix}$$

Control Design

Mathematical framework: AUV

- PT: Backstepping



Backstepping dynamics

$$\begin{cases} \tau_u = m_u \dot{u} - m_v v r + d_u u \\ 0 = m_v \dot{v} + m_u u r + d_v v \\ \tau_r = m_r \dot{r} - m_{uv} u v + d_r r \end{cases}$$

Virtual control inputs

$$z = \begin{pmatrix} z_{vt} \\ z_\omega \end{pmatrix} = \begin{pmatrix} v_t - \alpha_{vt} \\ \omega - \alpha_\omega \end{pmatrix}$$

$$V_{dyn} = V + \frac{1}{2} z^T M z \Longrightarrow \begin{cases} \tau_u = m_u(\dot{v}_t - f_{vt}) / \cos\beta = [m_u \dot{\alpha}_{v_t} + ((1-\lambda)x_e - k_{v_t} z_{v_t}) - m_u f_{vt}] / \cos\beta \\ \tau_r = m_r \dot{r} - m_{uv} u v + d_r r = m_r \dot{\alpha}_\omega + (\frac{1}{\gamma}\psi_e - k_\omega z_\omega) - m_{uv} u v + d_r r \end{cases}$$

Control Design

Mathematical framework: AUV

- Smooth transition between underactuated to fully-actuated

Underactated case: high speed

$$\tau_v = \begin{cases} \tau_{v1} = 0, \\ \tau_{v2} = \frac{m_v u}{\cos^2 \beta}\left[\frac{\sin^2 \beta}{m_u v}\tau_u - f_\beta + \dot{\beta}_d - k_5(\beta - \beta_d)\right] \end{cases}$$

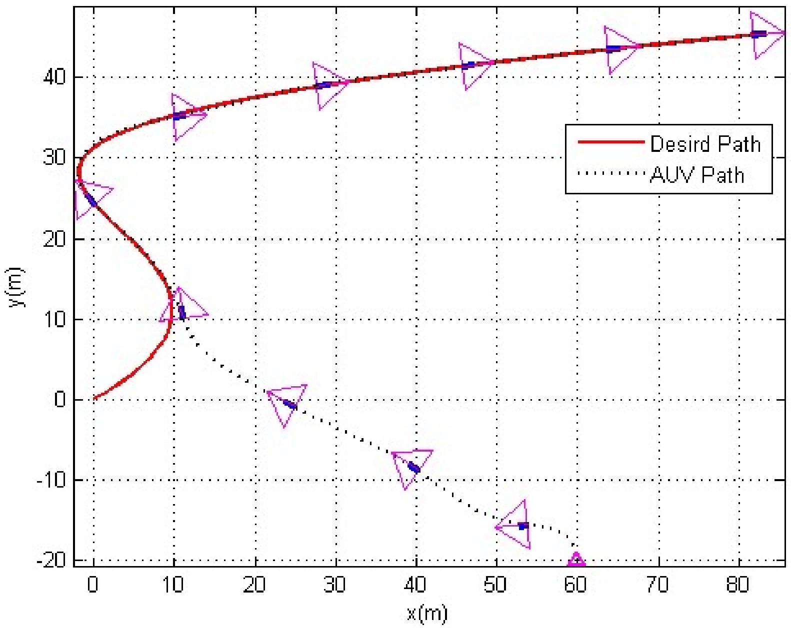
Fully-actuated case: low speed

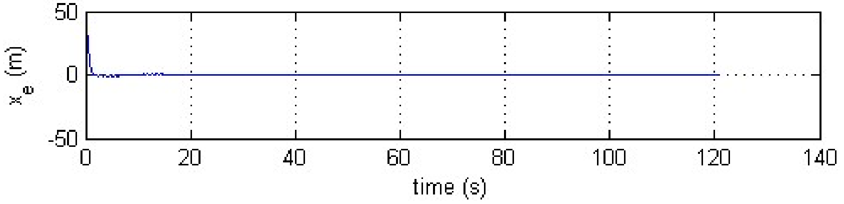
$$f(v_t) = \frac{\frac{\pi}{2} + \arcsin[k_{vt}(v_t - \frac{v_{t1}+v_{t2}}{2})/(\frac{v_{t2}-v_{t1}}{2})]}{\pi}$$

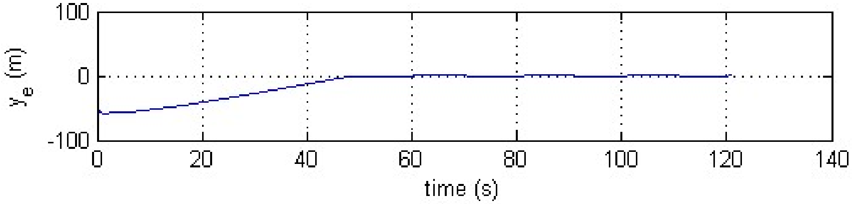
$$0 \leq f(v_t) \leq 1$$

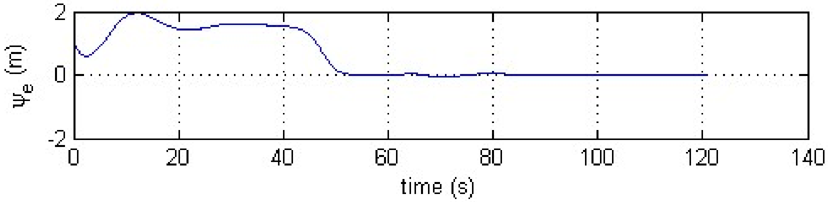
$$\tau_v = f(v_t)\tau_{v1} + (1 - f(v_t))\tau_{v2}$$

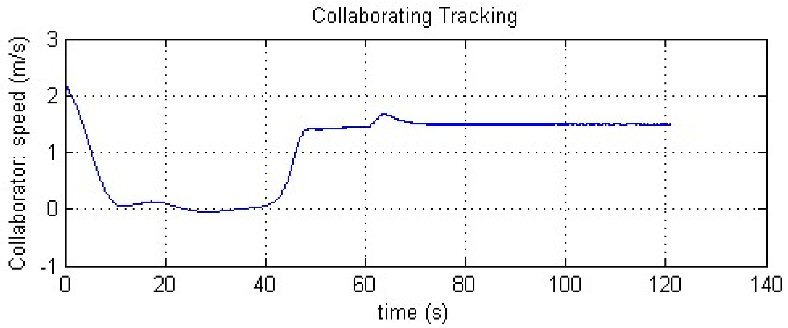
Control examples: Path Following

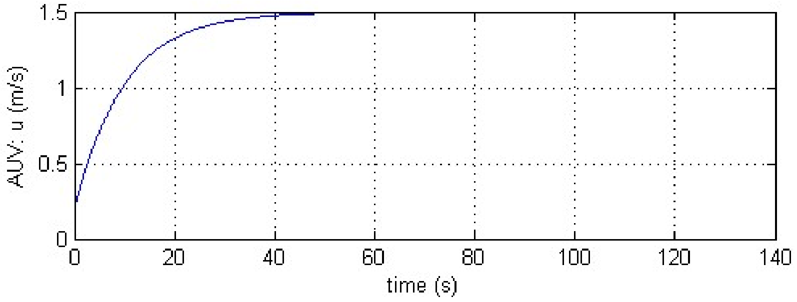


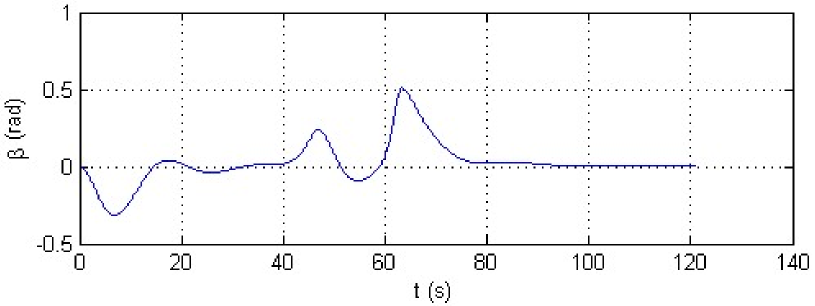


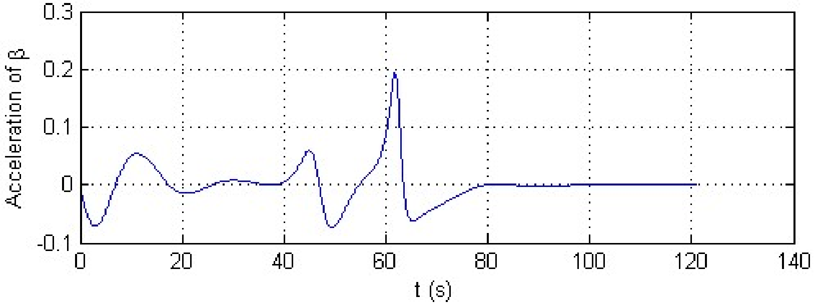




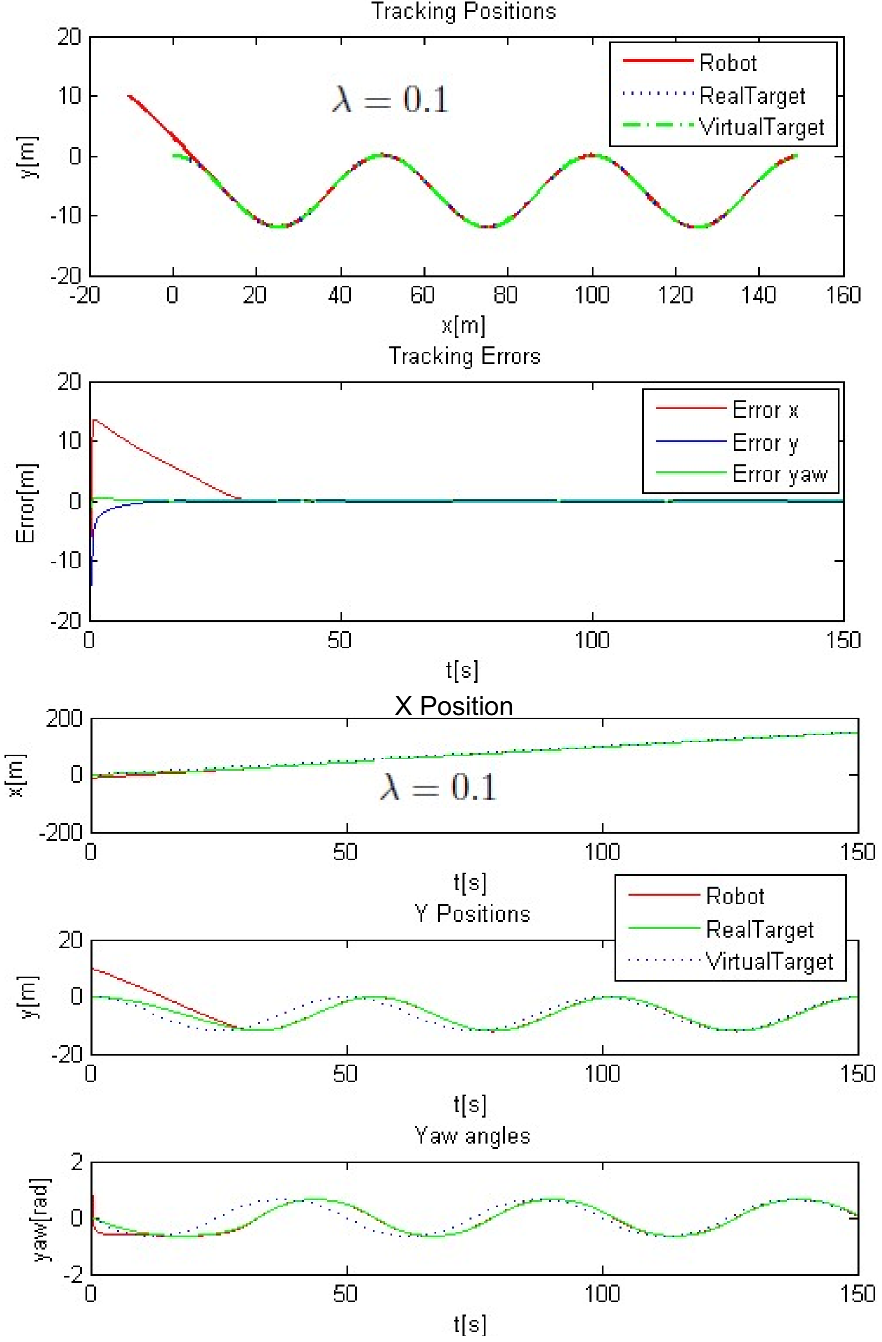


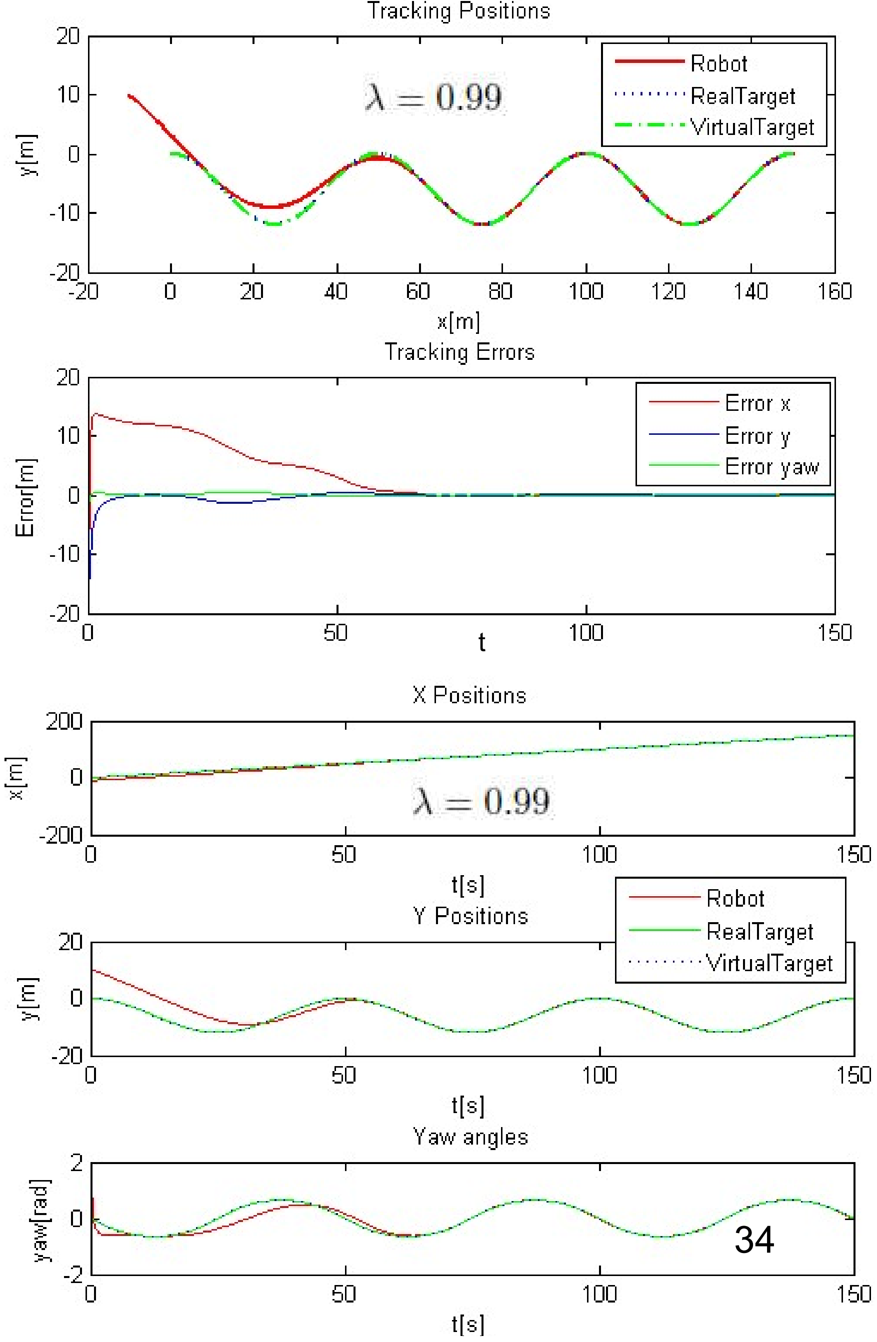






Control examples: Path Tracking





Summary

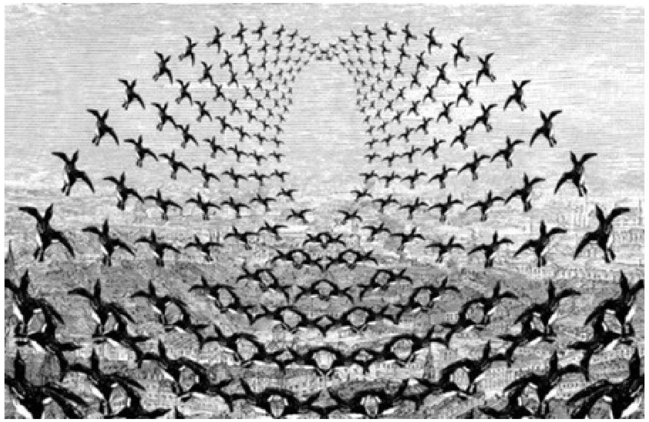
Motion control of single vehicle

1. Problem pose - analyze the main methods
2. Novel control design
3. From unicycle to AUV (simple to complex)
4. Smooth transition from under to fully actuated AUV

Coordination: multiple vehicles

Approach: the state-of-the-art

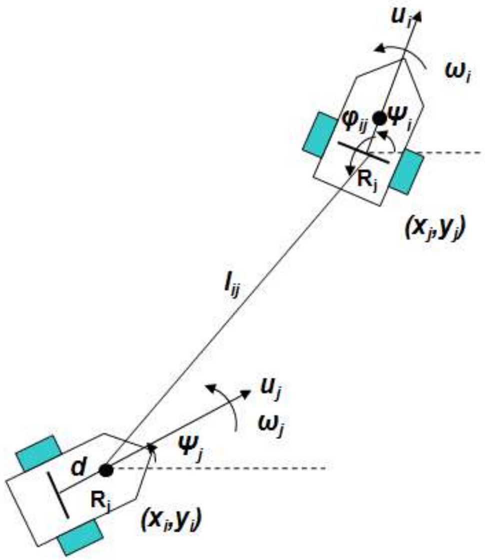
Behavioral-based [Balch&Arkin 1998]

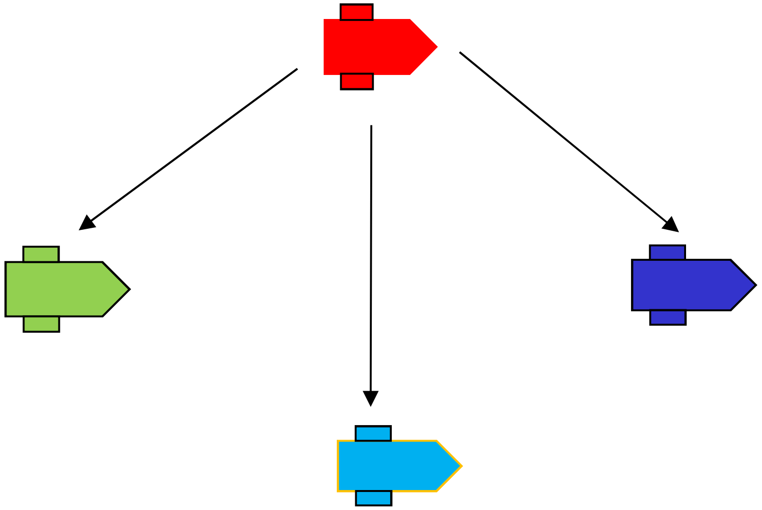


Coordination: multiple vehicles

Approach: the state-of-the-art

Leader-follower [Desai 2001]

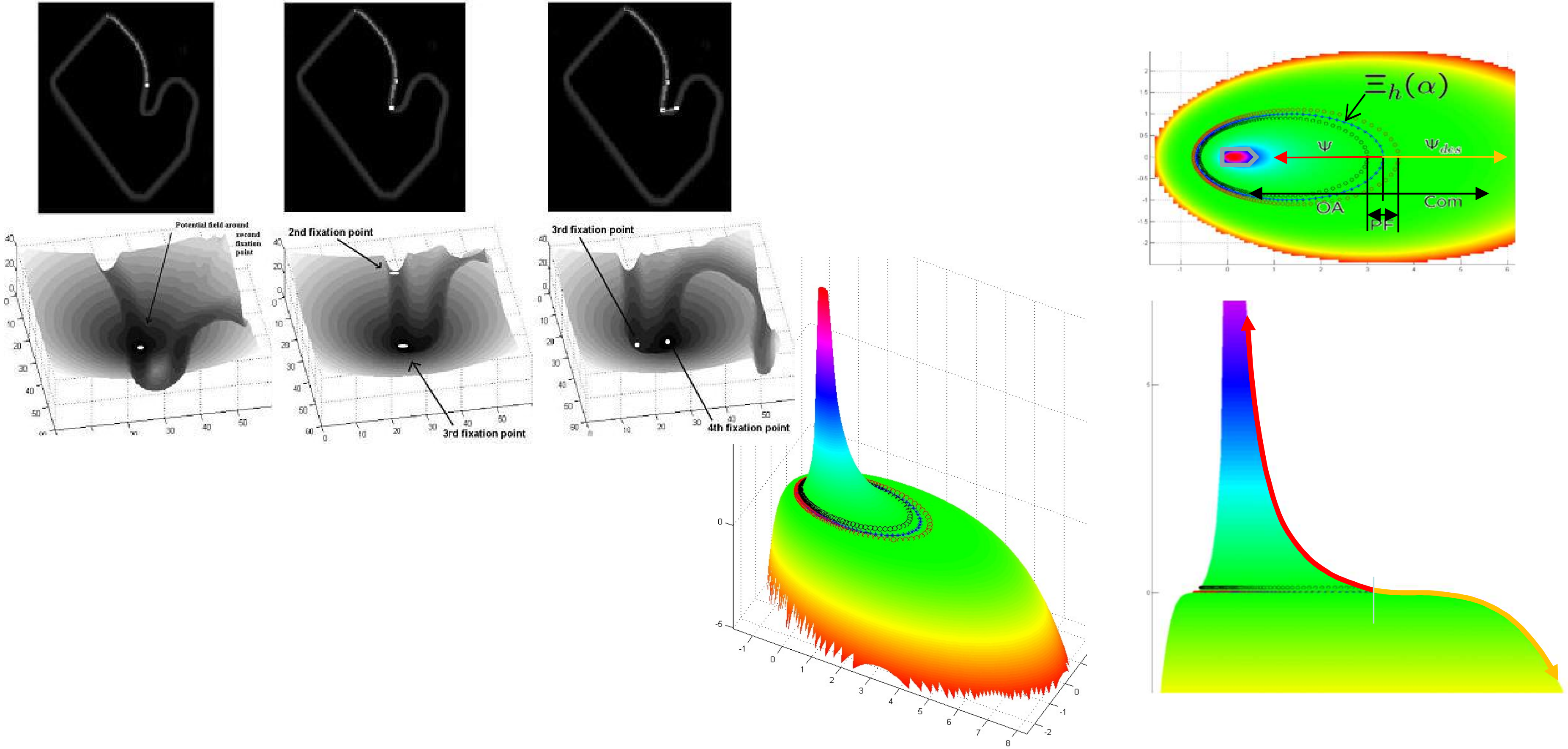




Coordination: multiple vehicles

Approach: the state-of-the-art

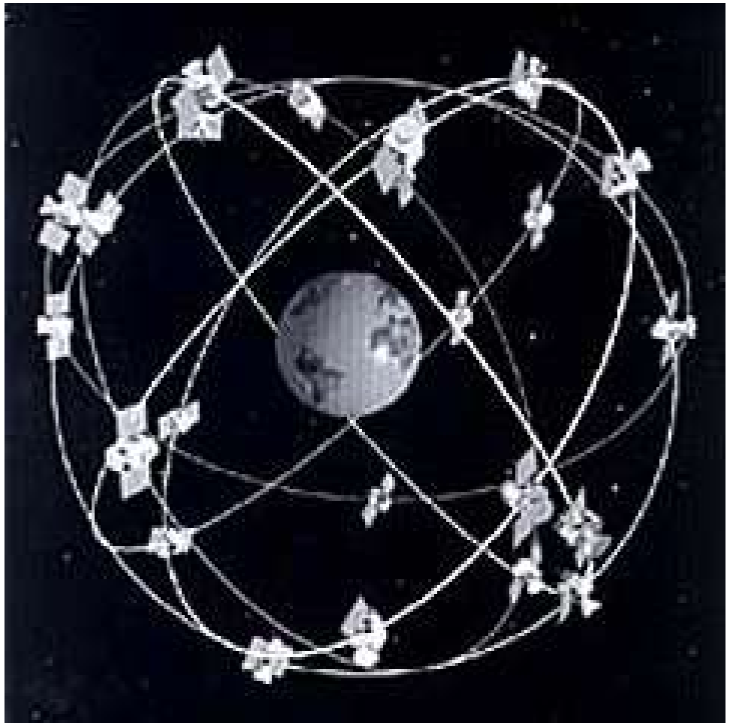
Artificial potential [Leonard&Fioerelli 2001]

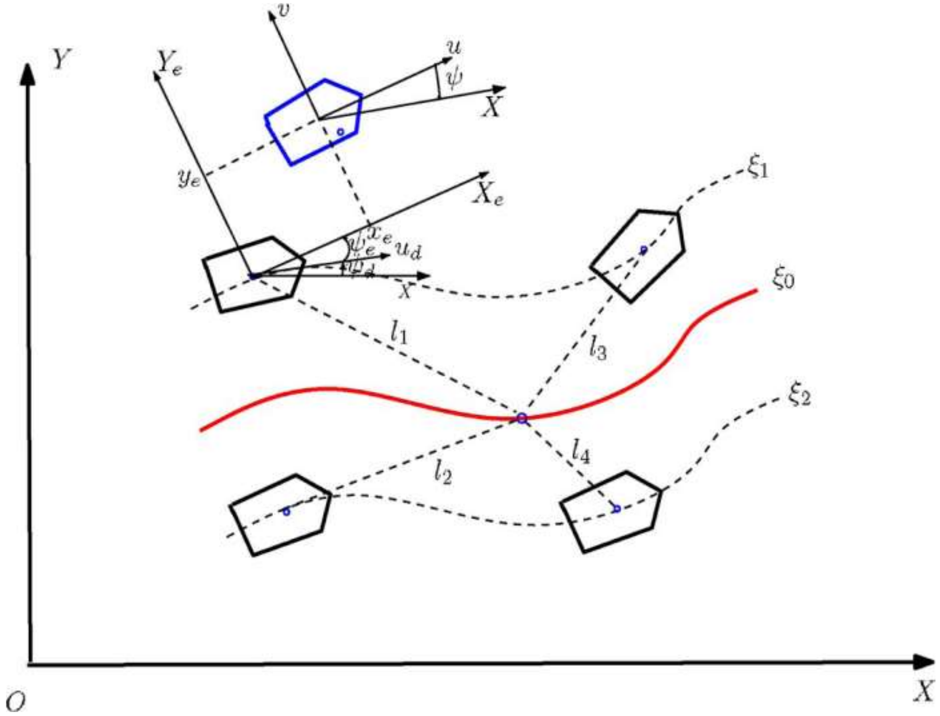


Coordination: multiple vehicles

Approach: the state-of-the-art

Virtual structure [Kang&Yeh 2002]





Coordination: multiple vehicles

Approach: the state-of-the-art

Approaches	Advantage	Disadvantage	Control design
Behavioral-based [Balch&Arkin, 1998]	Intuitive	Behavior description	Algorithmic
Leader-follower [Desai 2001]	Unique reference	Single-point failure	Formal
Artificial potential [Leonard&Fioerelli 2001]	Collision-free	Local minimum	Formal*
Virtual structure [Kang&Yeh,2002]	Rigid	Not flexible	Formal

Coordination: multiple vehicles

Approach: new proposition

1. Leader-follower

Centralized control

Decentralized control

2. Virtual Structure: Formation Reference Point (FRP)

Virtual target embedded

Touch the objective:

Coordinated Paths Following (CPF)

Coordinated Paths Tracking   (CPT)

What's the detailed strategy ?

How to implement the approach?

Coordination: multiple vehicles

Strategy:

‘*Shared information is a necessary condition for coordination*’

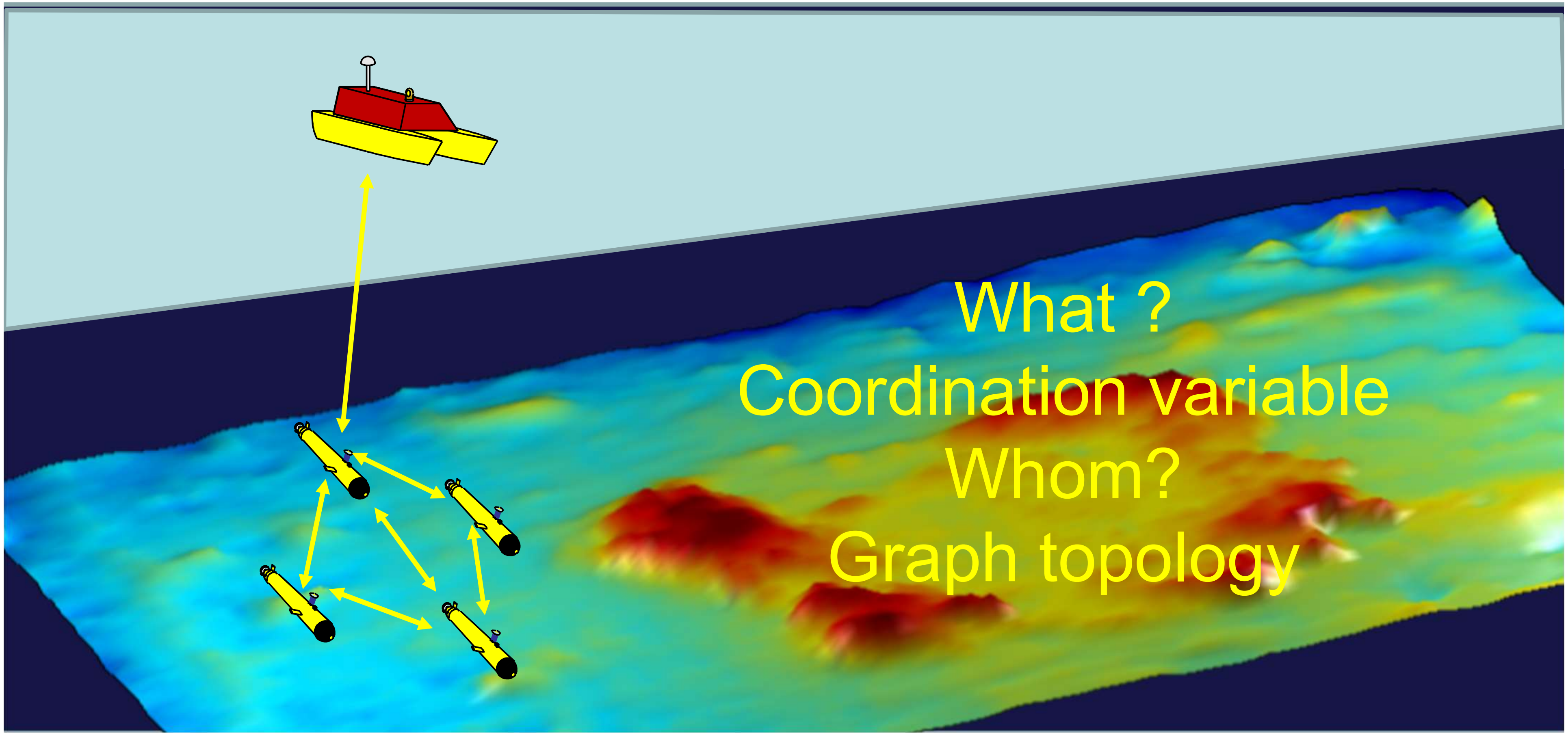
[Ren 2005]

Coordination: multiple vehicles

Strategy:

Q1) What kind of information should be shared?

Q2) Which one should share information with?



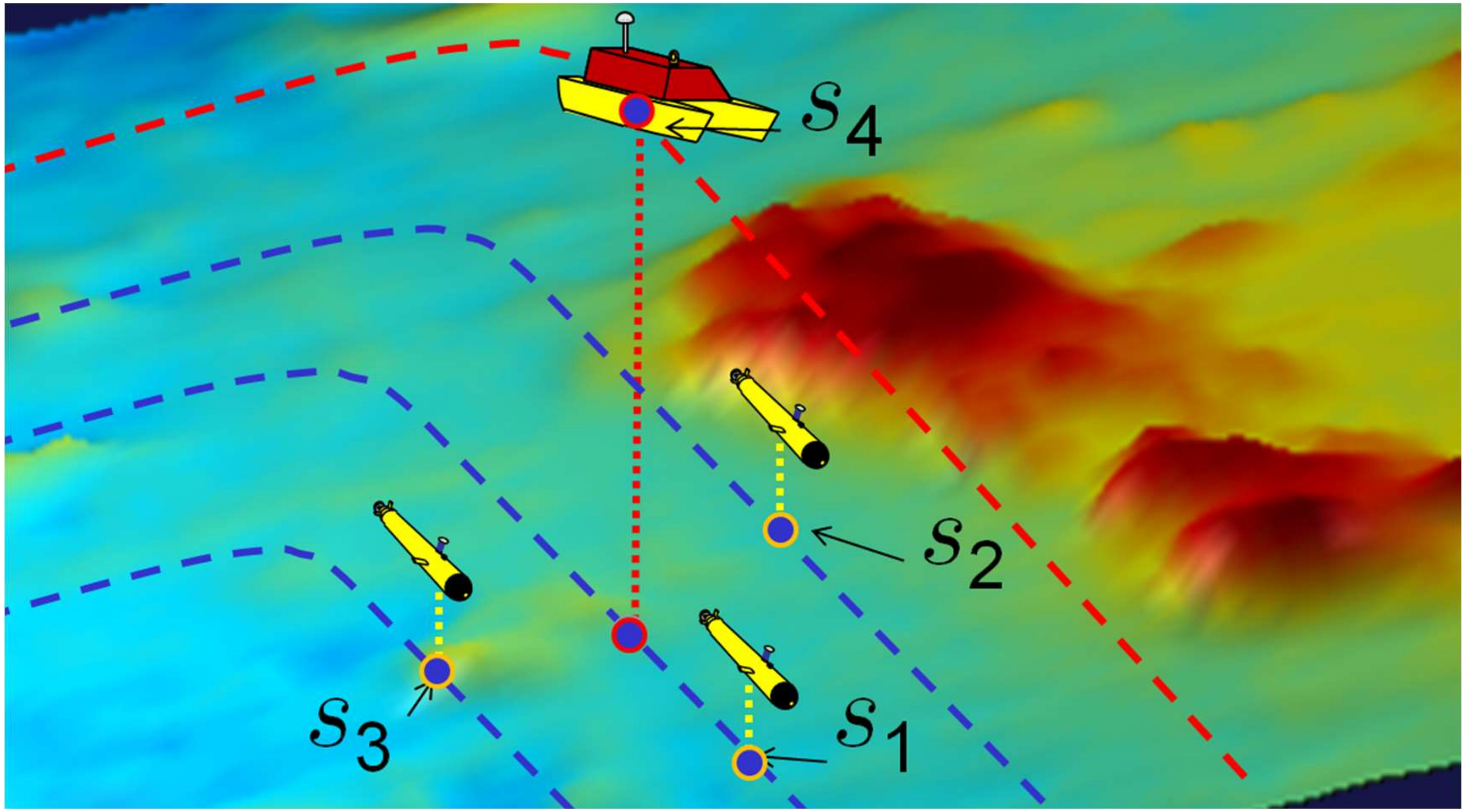
Coordination: multiple vehicles

Strategy: Coordinated Paths Following (**CPF)**

Q1) What kind of information should be shared?

Coordination variable : the virtual target

(along path distance)



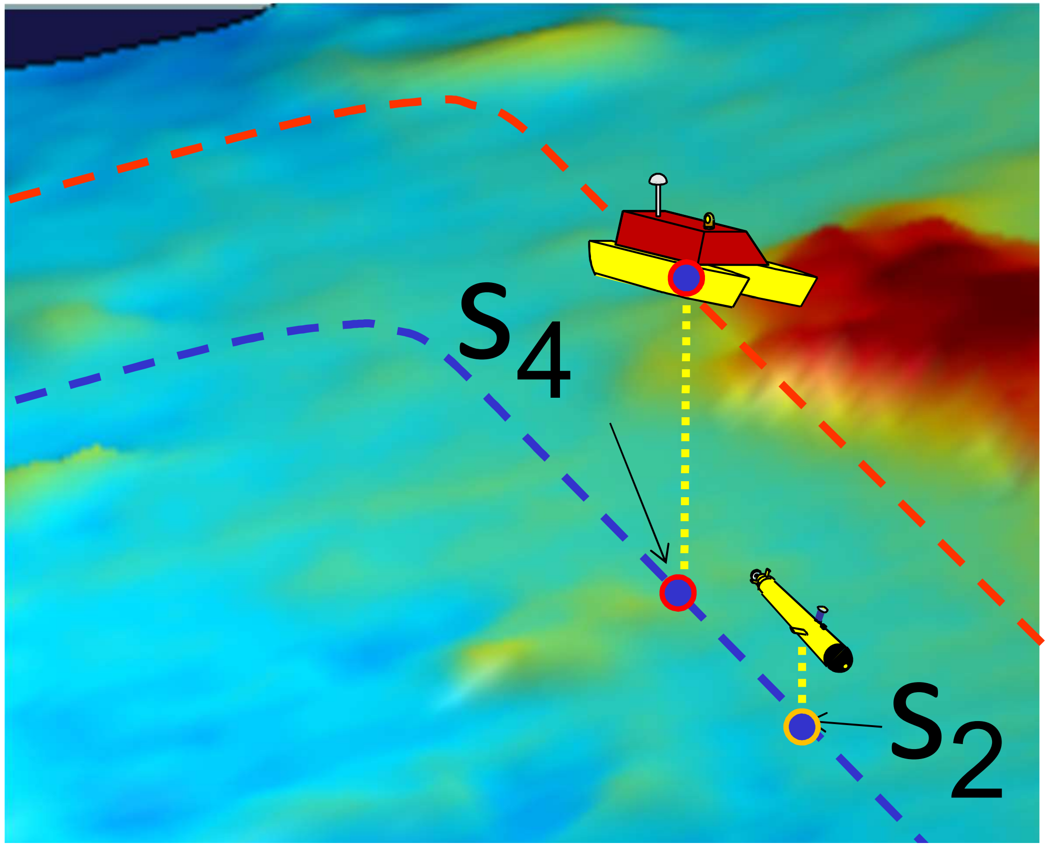
5. Coordination: multiple vehicles

Strategy: Coordinated Paths Following (**CPF**)

Q1) What kind of information should be shared?

Coordination variable : the virtual target

(along path distance)



Shifted paths:

$$\Delta s = s_2 - s_4$$

Adapt u_2 and u_4:

$$\Delta s \rightarrow \Delta_s^d$$

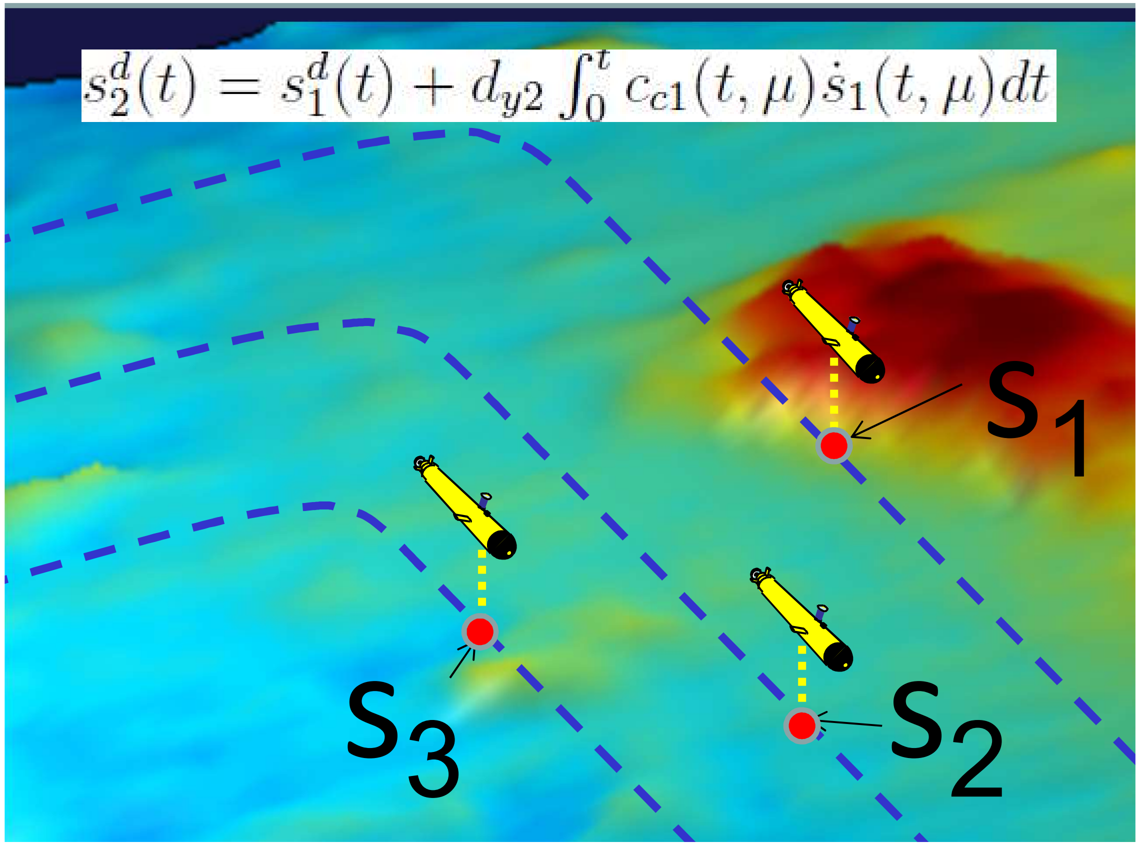
Coordination: multiple vehicles

Strategy: Coordinated Paths Following (**CPF)**

Q1) What kind of information should be shared?

Coordination variable : the virtual target

(**normalized** along path distance)



$$s_2^d(t) = s_1^d(t) + d_{y2} \int_0^t c_{c1}(t,\mu)\dot{s}_1(t,\mu)dt$$

Parallel paths

(but feasible)

$$\Delta s_i = s_i - s_i^d$$

Adapt u_i, such that:

$$\Delta s_i \rightarrow \Delta_{s_i}^d$$

Coordination: multiple vehicles

Strategy: Coordinated Paths Following (**CPF)**

Q1) What kind of information should be shared?

Coordination variable : the virtual target

(**normalized** along path distance)

Arbitrary paths

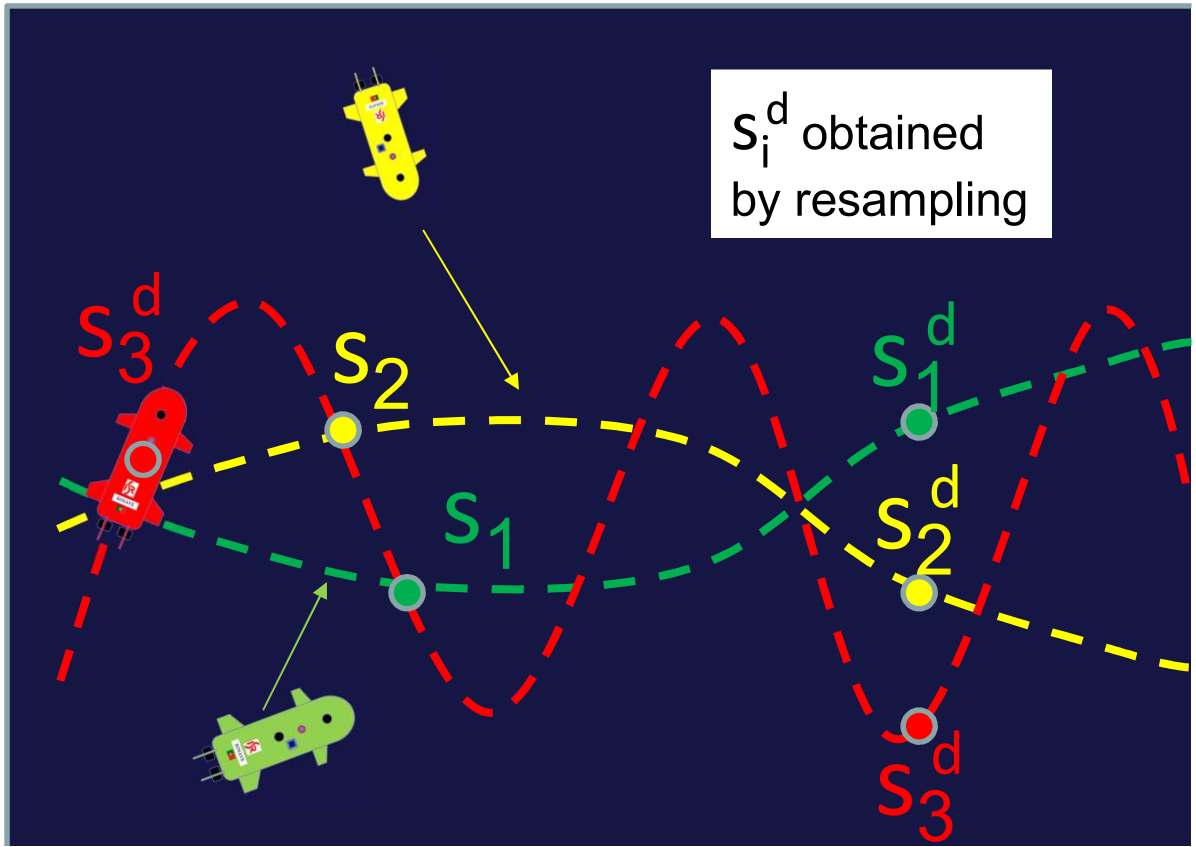
(but feasible)

$$\Delta s_i = s_i - s_i^d$$

Adapt u_i,

such that:

$$\Delta s_i \rightarrow \Delta_{s_i}^d$$



s_i^d obtained by resampling

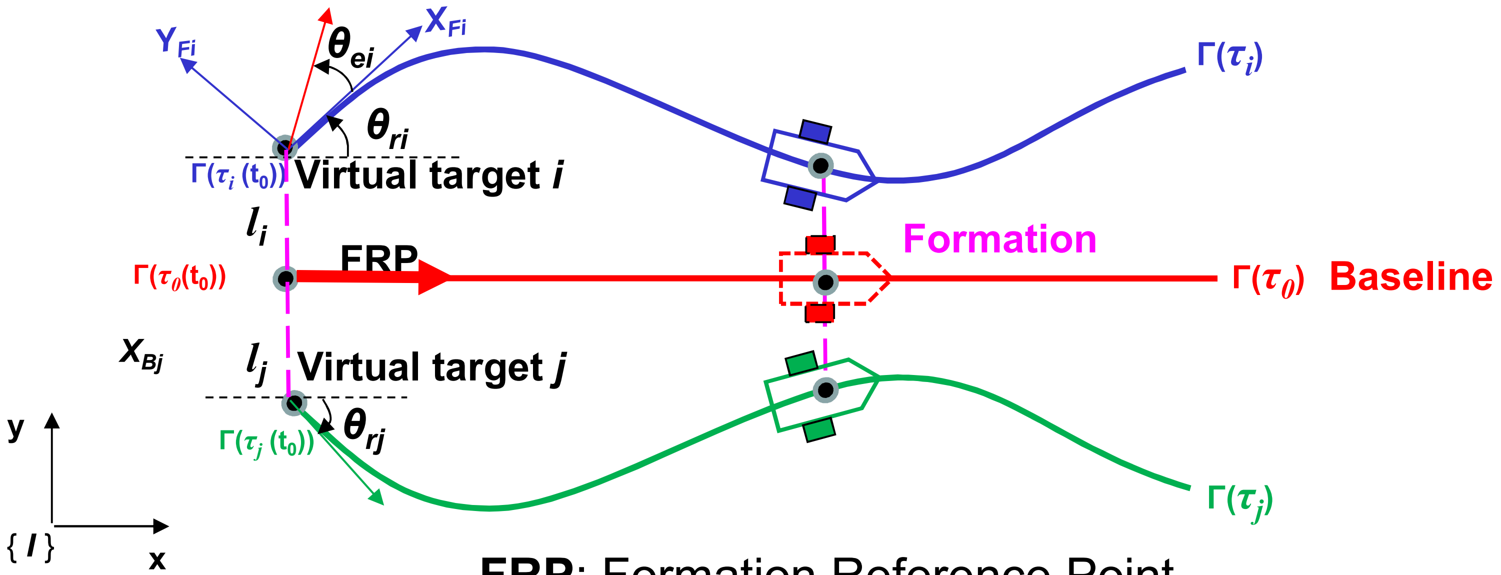
Coordination: multiple vehicles

Strategy: **Coordinated Path Tracking (CPT)**

Q1) What kind of information should be shared?

Coordination variable : the virtual target

(along path position)



FRP: Formation Reference Point

Paths formulation: $\Gamma_i(\tau_i)|_{\{I\}} = \Gamma_{r0}(\tau_i)|_{\{I\}} + R(\psi_{r0}(\tau_i))|_{\{F\}}^{\{I\}} l_i(x_{r0}(\tau_i), y_{r0}(\tau_i))|_{\{F\}}$

Baseline **Rotation matrix** **Shifted vector**

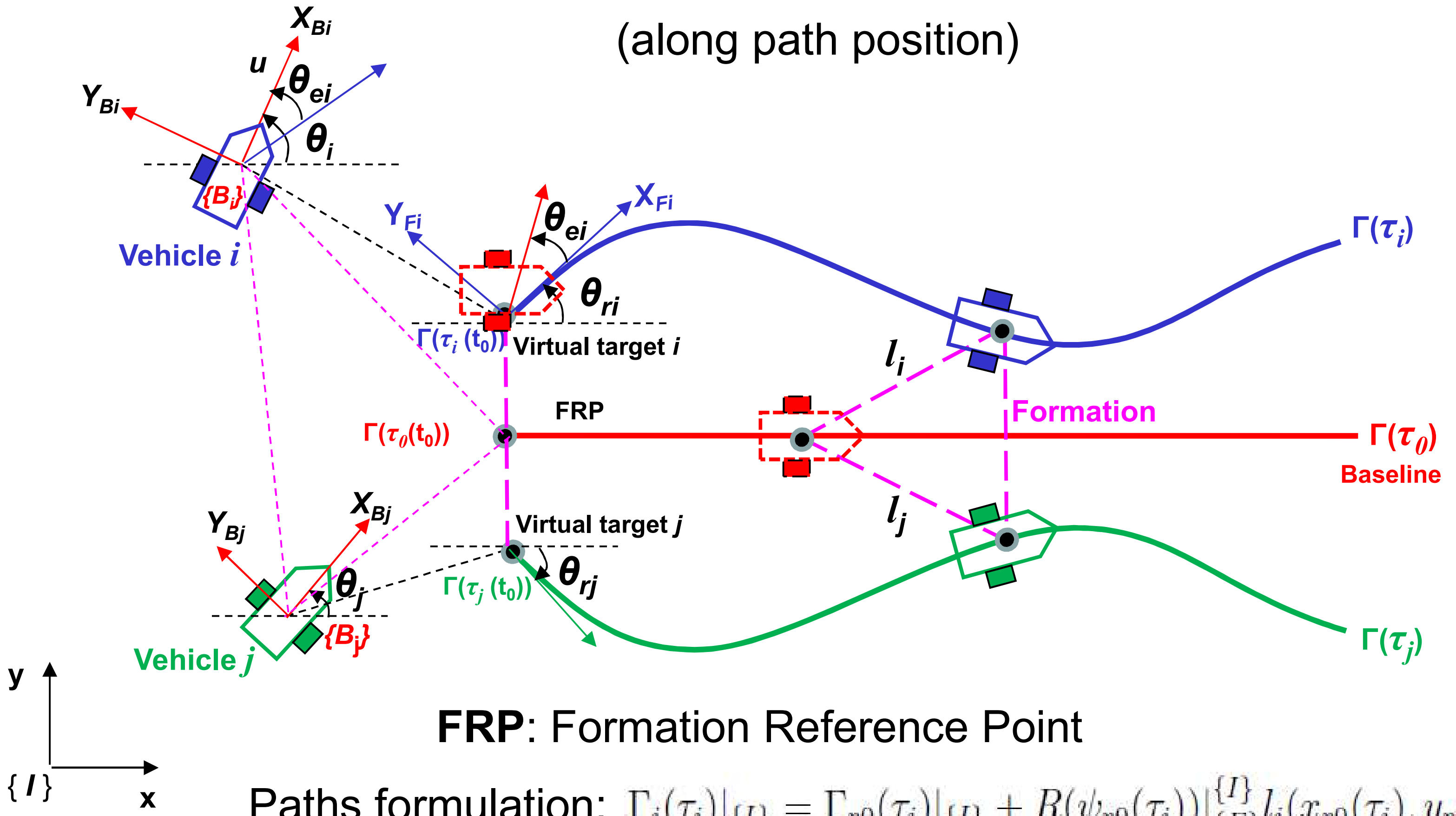
Coordination: multiple vehicles

Strategy: **Coordinated Path Tracking (CPT)**

Q1) What kind of information should be shared?

Coordination variable : the virtual target

(along path position)



FRP: Formation Reference Point

Paths formulation: $\Gamma_i(\tau_i)|_{\{I\}} = \Gamma_{r0}(\tau_i)|_{\{I\}} + R(\psi_{r0}(\tau_i))|_{\{F\}}^{\{I\}} l_i(x_{r0}(\tau_i), y_{r0}(\tau_i))|_{\{F\}}$

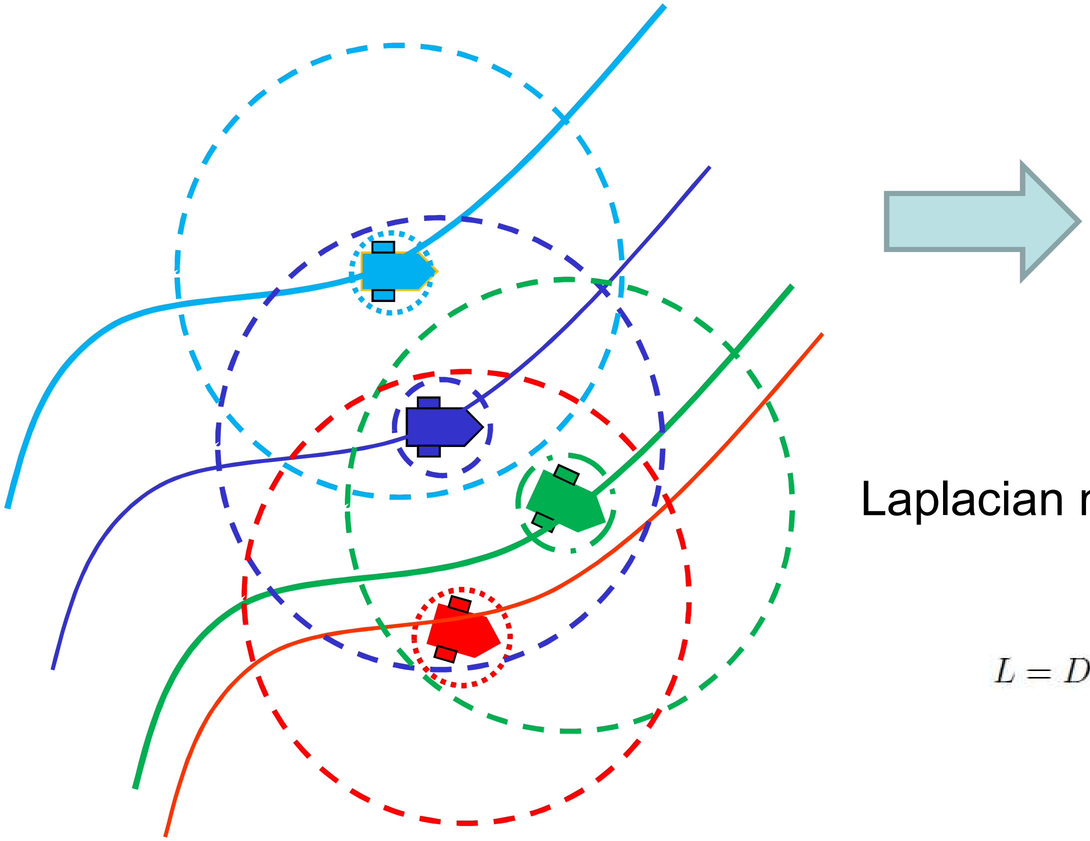
Baseline **Rotation matrix** **Shifted vector**

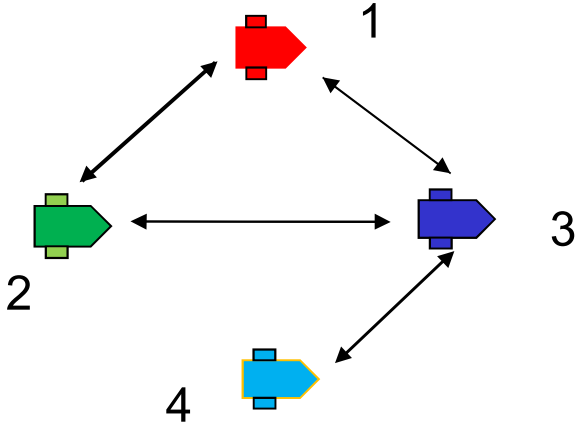
Coordination: multiple vehicle

Strategy:

Q2) Which one should share information with?

Communication Topology: graph representation





Laplacian matrix *L*:

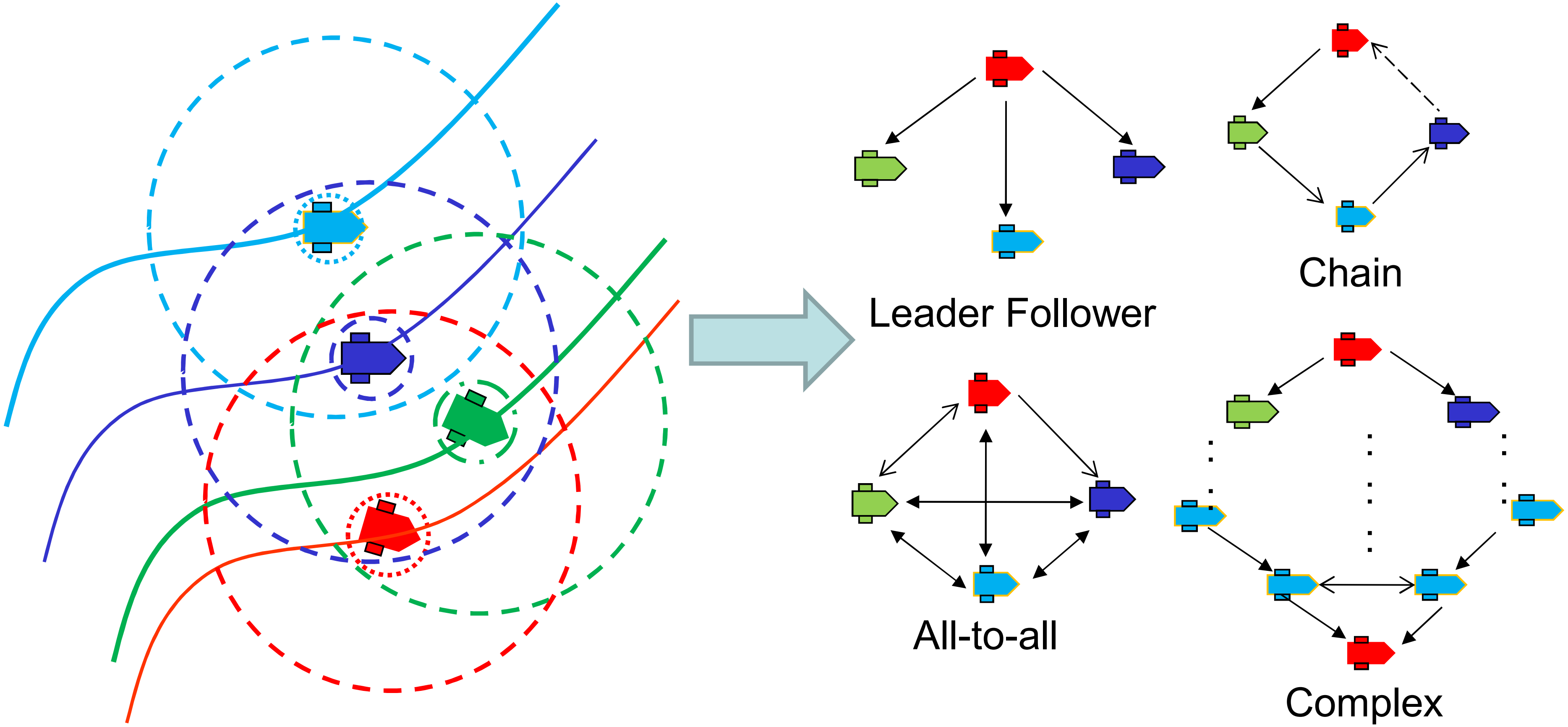
$$L = D - A = \begin{array}{cccc|c} 1 & 2 & 3 & 4 & \\ 2 & -1 & -1 & 0 & 1 \\ -1 & 2 & -1 & 0 & 2 \\ -1 & -1 & 3 & -1 & 3 \\ 0 & 0 & -1 & 1 & 4 \end{array}$$

Coordination: multiple vehicles

Strategy:

Q2) Which one should share information with?

Communication Topology: graph representation



Coordination: multiple vehicles

Summary the strategy for Q1&Q2:

Q1: What kind of information should be shared?

A1: Normalized along path distance (CPF)

Along path position (CPT)

Q2: Which one should share information with?

A2: all-to-all, broadcasting, neighborhood communication…

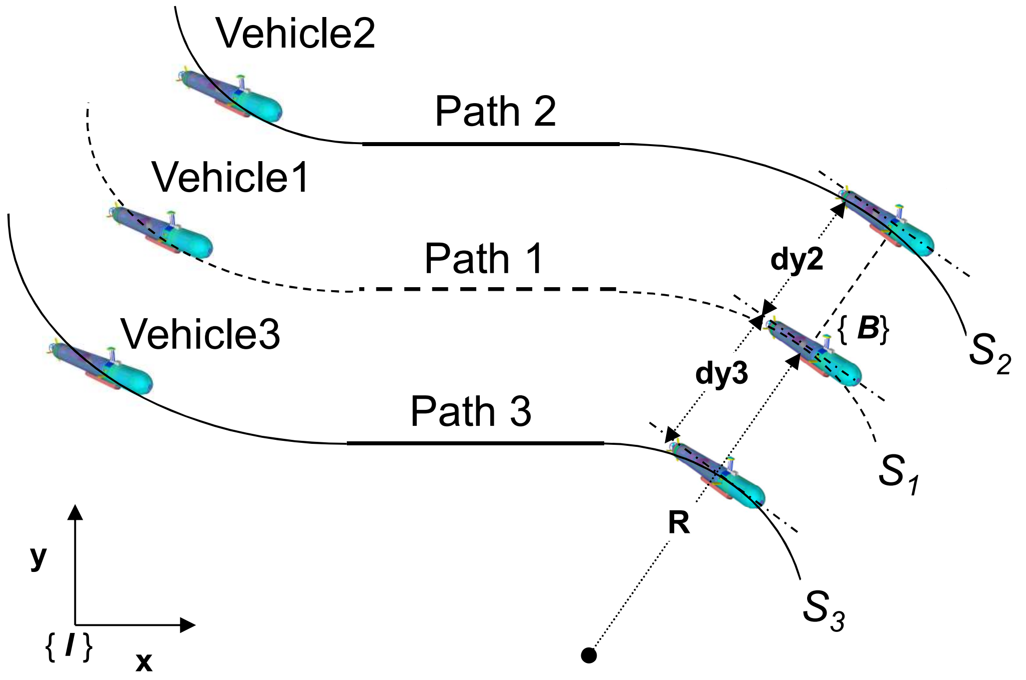
Ready for starting the control design!!!

Coordination: multiple vehicle

Control design: Coordinated paths following

Methods: formation leaded by virtual targets

Leader-follower



Objective: $s_i = s_i^d$

$$s_i^d = s_j^d$$

$$V_s = \frac{1}{2}\Delta S_{LFi}^2$$

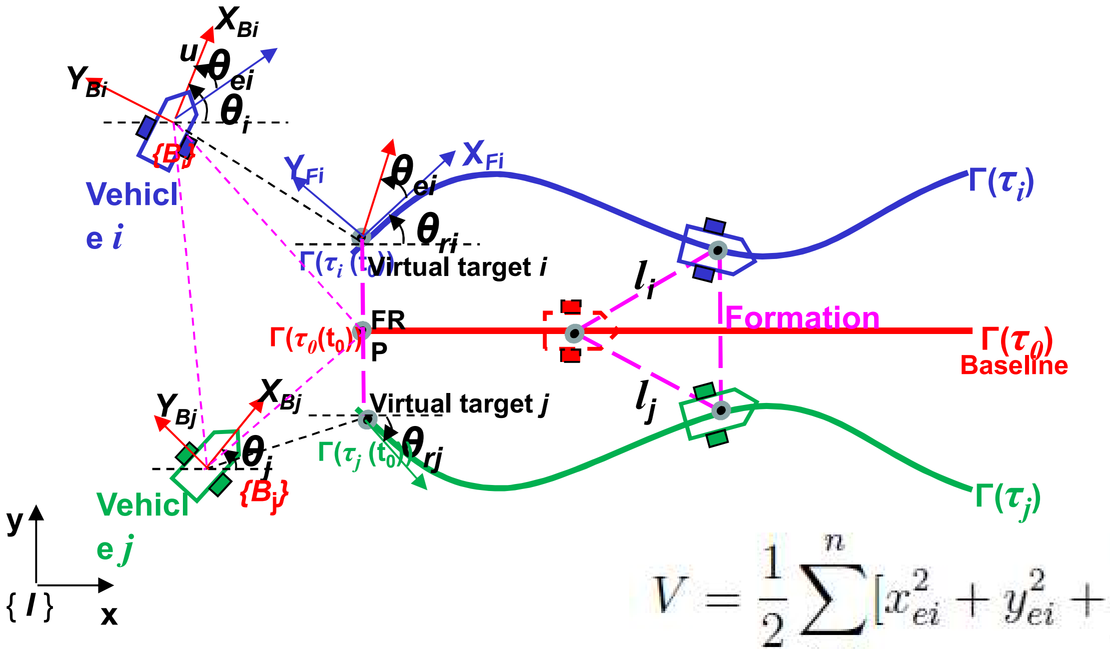
Speed adaptation:

$$u_{F1}^d = u_L^d + \frac{2}{\pi} k_u \arctan(\Delta s_{LF1})$$

Coordination: multiple vehicle

Control design: Coordinated paths tracking

1) Centralized control via FRP



Objective:

1) Geometric assignment

$$\lim_{t\to\infty} \|P_{eiB}\| = 0$$

2) Temporal assignment

$$\lim_{t\to\infty} |\tau_i(t) - \tau_0(t)| = 0$$

$$V = \frac{1}{2}\sum_{i=1}^{n}\left[x_{ei}^2 + y_{ei}^2 + \frac{1}{\gamma}(\theta_{ei} - \delta_i)^2\right] + \frac{1}{2}\sum_{i=1}^{n} k_\tau(\tau_i - \tau_0)^2$$

Control input:

$$\begin{bmatrix} u_i \\ \omega_i \\ \dot{\tau}_i \end{bmatrix} = \begin{bmatrix} k_1 x_{ei} + \bar{u}_{ri}\dot{\tau}_0 \cos\theta_{ei} \\ \bar{\omega}_{ri}\dot{\tau}_0 - \dot{\delta}_i + \gamma y_{ei}\bar{u}_{ri}\dot{\tau}_0 \frac{\sin\theta_{ei} - \sin\delta_i}{\theta_{ei} - \delta_i} + k_\theta(\theta_{ei} - \delta_i) \\ \dot{\tau}_0 - k_v \tanh(\Phi_{Ei}) \end{bmatrix}$$

Formation
Feedback on FRP

$$\dot{\tau}_0 = \omega_0(t)\left(1 - k_f \tanh\left(\sum_{i=1}^{n} P_{eiB}^T W P_{eiB}\right)\right)$$

Coordination: multiple vehicle

Control design: Coordinated paths tracking

2) Centralized control via individual vehicle(not the FPR)

Objective:

1) Geometric assignment

$$\lim_{t\to\infty} \|P_{eiB}\| = 0$$

2) Temporal assignment

$$\lim_{t\to\infty} |\tau_i(t) - \tau_0(t)| = 0$$

CLF:

$$V = \frac{1}{2}\sum_{i=1}^{n}[x_{ei}^2 + y_{ei}^2 + \frac{1}{\gamma}(\theta_{ei} - \delta_i)^2] + \frac{1}{2}\sum_{i=1}^{n} k_\tau(\tau_i - \tau_0)^2$$

Control input:

$$\begin{bmatrix} u_i \\ \omega_i \\ \dot{\tau}_i \end{bmatrix} = \begin{bmatrix} k_1 x_{ei} + \bar{u}_{ri}\dot{\tau}_0 \cos\theta_{ei} \\ \bar{\omega}_{ri}\dot{\tau}_0 - \dot{\delta}_i + \gamma y_{ei}\bar{u}_{ri}\dot{\tau}_0 \frac{\sin\theta_{ei} - \sin\delta_i}{\theta_{ei} - \delta_i} + k_\theta(\theta_{ei} - \delta_i) \\ \dot{\tau}_0 - k_v \sum_{i=1}^{n} \Phi_{Ei} \end{bmatrix}$$

Formation feedback

$$\dot{V} = \sum_{i=1}^{n}[-k_e x_{ei}^2 + y_{ei}\bar{u}_{ri}\dot{\tau}_0 \sin\delta_i - \frac{k_\theta}{\gamma}(\theta_{ei} - \delta_i)^2] - k_v(\sum_{i=1}^{n} \Phi_{Ei})^2$$

$$\dot{V} = \sum_{i=1}^{n}[-k_e x_{ei}^2 - k_v \Phi_{Ei} \tanh(\Phi_{Ei}) + y_{ei}\bar{u}_{ri}\dot{\tau}_0 \sin\delta_i - \frac{k_\theta}{\gamma}(\theta_{ei} - \delta_i)^2]$$

Coordination: multiple vehicle

Control design: Coordinated paths tracking

3) decentralized controller

Objective:

1) Geometric assignment

$$\lim_{t\to\infty} \|P_{eiB}\| = 0$$

2) Temporal assignment

$$\lim_{t\to\infty} |\tau_i(t) - \tau_j(t)| = 0$$

Challenge: how to embed the graph theory in the control frame

$$V = \frac{1}{2}\sum_{i=1}^{n}[x_{ei}^2 + y_{ei}^2 + \frac{1}{\gamma}(\theta_{ei} - \delta_i)^2]$$

$$\dot{\tau}_i = \dot{\tilde{\tau}}_i + v_{\tau i}$$

$$V_{aug} = V + \frac{1}{2}\Omega_\tau^T K_1^{-1} K_2^{-1} \Omega_\tau + \frac{1}{2}\mathcal{T}^T L \mathcal{T}$$

$$\begin{aligned} \Omega_\tau &= [\dot{\tilde{\tau}}_1, \ldots, \dot{\tilde{\tau}}_n]^T \\ \mathcal{T} &= [\tau_1, \ldots, \tau_n]^T \end{aligned}$$

Decentralized controller:

$$\begin{cases} \dot{\tau}_i = \dot{\tilde{\tau}}_i + v_{\tau_i} \\ \ddot{\tilde{\tau}}_i = -k_{1i}[\dot{\tilde{\tau}}_i + k_{2i}(\sum_{j\in J_i}(\tau_i - \tau_j) + \phi_i)] \end{cases}$$

Coordination: multiple vehicle

Examples:

- CPF:

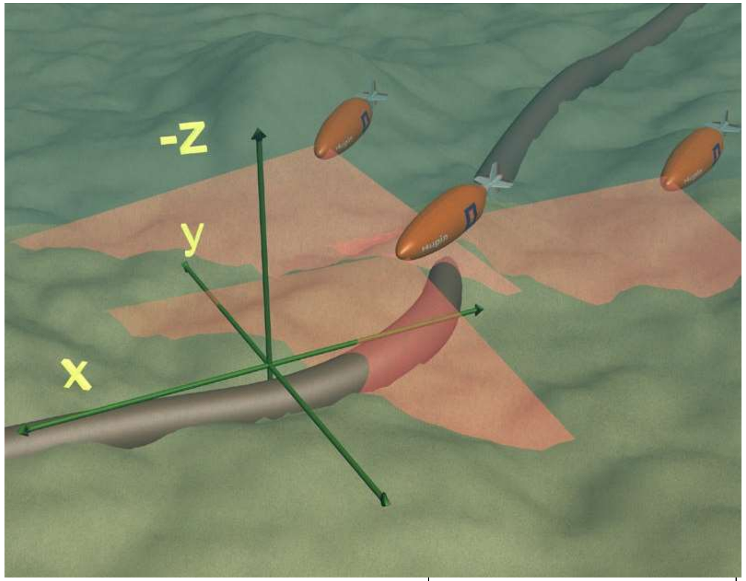
Centralized V.S. Decentralized control

- CPT:

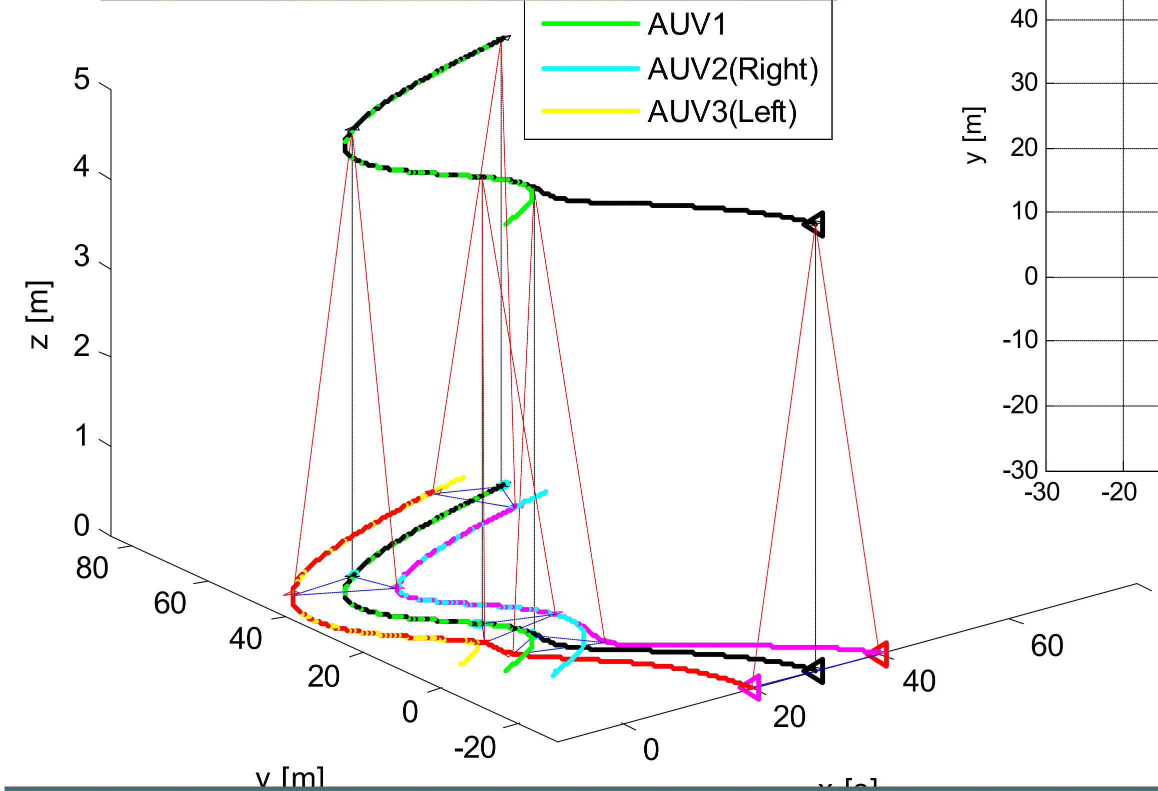
Decentralized

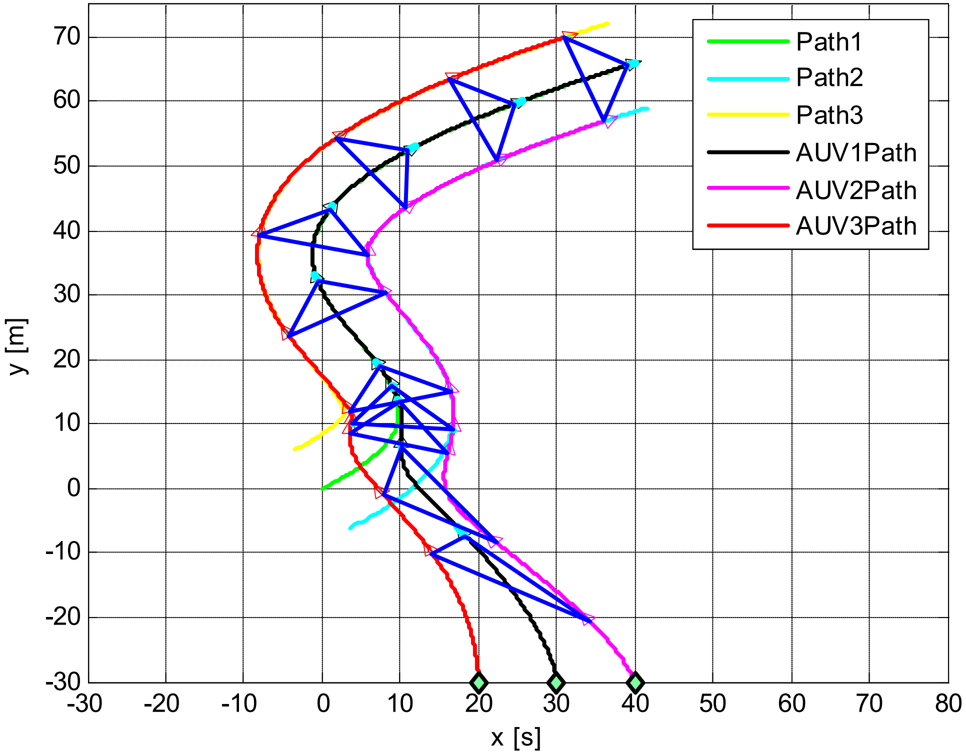
Triangle formation

Shrunk circle formation

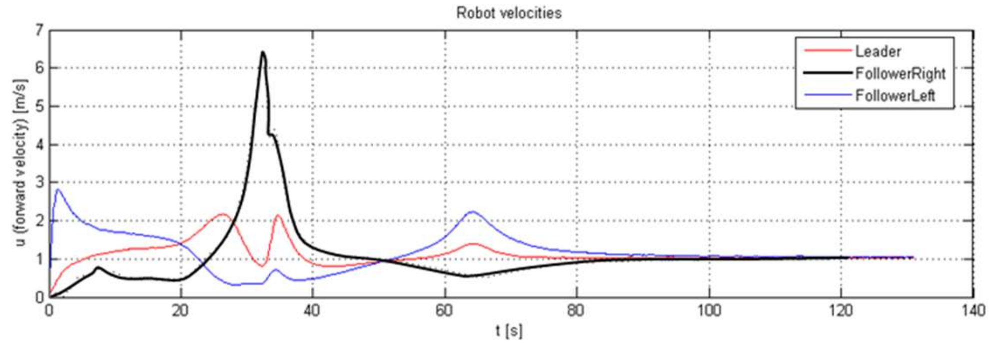


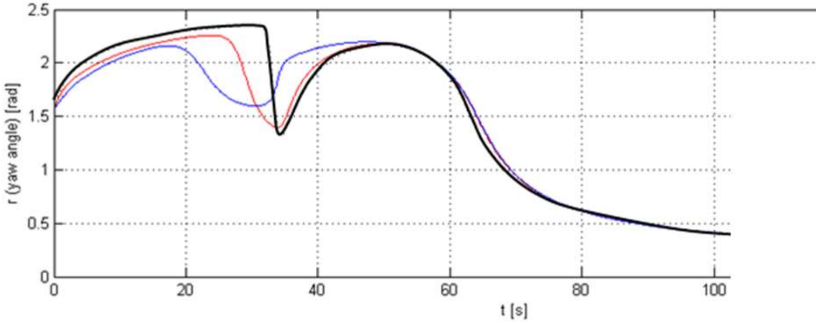
Coordinated Paths Following

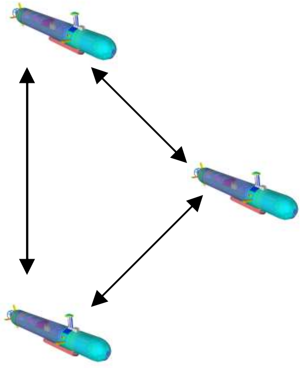


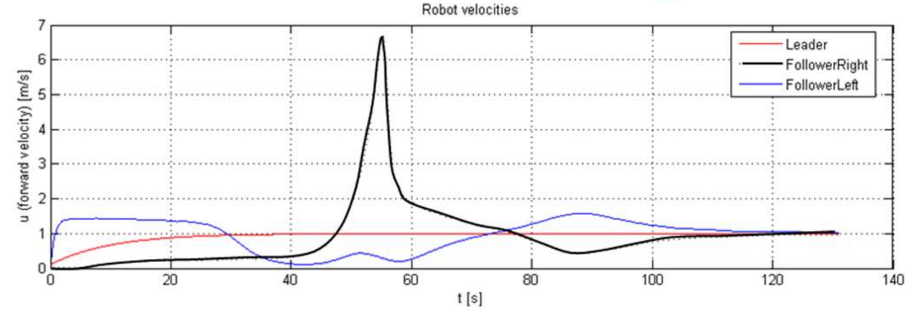


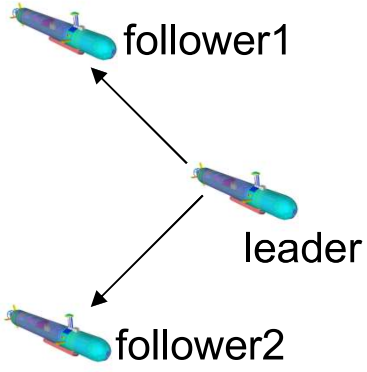
Coordinated Paths Following : in line formation

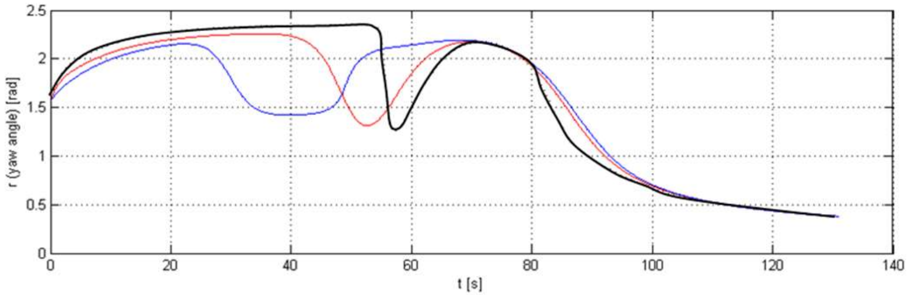








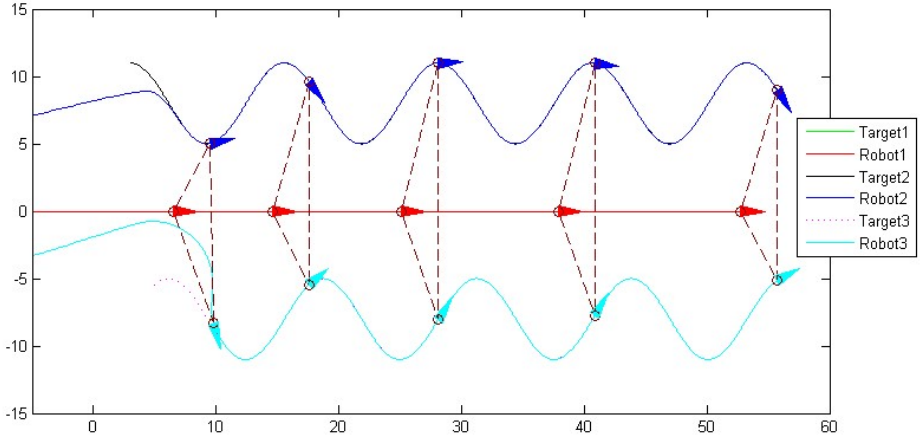




Coordination: multiple vehicle

Coordinate paths tracking

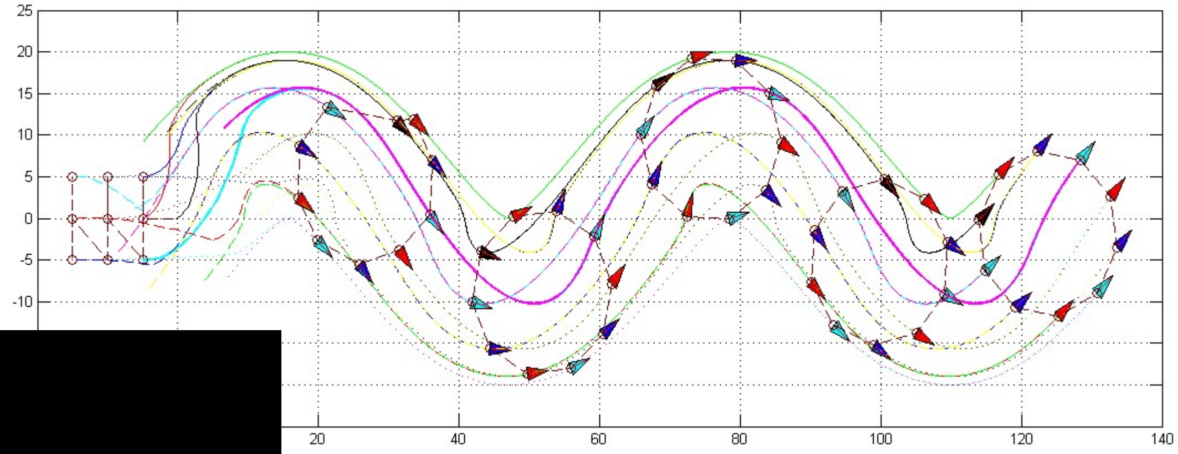
Triangle formation



Coordination: multiple vehicle

Coordinated paths tracking

Shrunk circle formation



Coordination: multiple vehicle

Summary:

1. Virtual target is the key for coordination

2. CPF: mathematical way to find relationship

3. CPT: more flexible

   Also solve the RDV problem

4. Graph theory: mathematical tool for comm. topology

Conclusion and prospective

Main achievements:

1. Path tracking

2. Coordinated paths following

3. Coordinated paths tracking (Rendezvous)

Conclusion and prospective

Prospective/Open problems:

1. 2D- 3D motion control:

2. Output feedback control: Observer

3. Communication issues

Uni-directional communication

Time-delays/packet loss/intermittent communication

4. Integration: PF/PT & Obstacle Avoidance

Demonstrations

Conclusion and prospective

Outputs– Publication lists

Journal:

- Xianbo Xiang, Bruno Jouvencel, Olivier Parodi. Coordinated formation control of multiple autonomous underwater vehicles for pipeline inspection, *International Journal of Advanced Robotic Systems*, Vol.7. No.1, 2010. pp 75-84

Book chapter:

- Xianbo Xiang, Lionel Lapierre, Bruno Jouvencel, Guohua Xu and Xinhan Huang. Chapter: Cooperative Acoustic Navigation Scheme for Heterogenous Autonomous Underwater Vehicles. *Underwater Vehicles,* ISBN: 978-953-7619-49-7, Publisher: InTech,2009

Conferences:

- Xianbo Xiang, Lionel Lapierre, Bruno Jouvencel. Guidance Based Collision Avoidance of Coordinated Nonholonomic Autonomous Vehicles, *Proceedings of 2010 IEEE International Conference on Intelligent Robots and Systems (IROS 2010)*.

- Xianbo Xiang, Lionel Lapierre, Bruno Jouvencel. Guidance Based Collision Free and Obstacle Avoidance of Autonomous Vehicles under Formation Constraints, *Proceedings of 2010 IFAC 7th Symposium on Intelligent Autonmous Vehicles (IAV 2010)*.

- Xianbo Xiang, Lionel Lapierre, Bruno Jouvencel, Olivier Parodi. Coordinated Path following Control of Multiple Nonholonomic Vehicles, *Proceedings of Oceans '09 IEEE Bremen (OCEANS09),* pp 1-7.

- Xianbo Xiang, Lionel Lapierre, Bruno Jouvencel, Olivier Parodi. Coordinated Path Following Control of Multiple Wheeled Mobile Robots Through Decentralized Speed Adaptation*, Proceedings of 2009 IEEE International Conference on Intelligent Robots and Systems (IROS 2009),* pp 4547-4552.

Thanks for your attention!