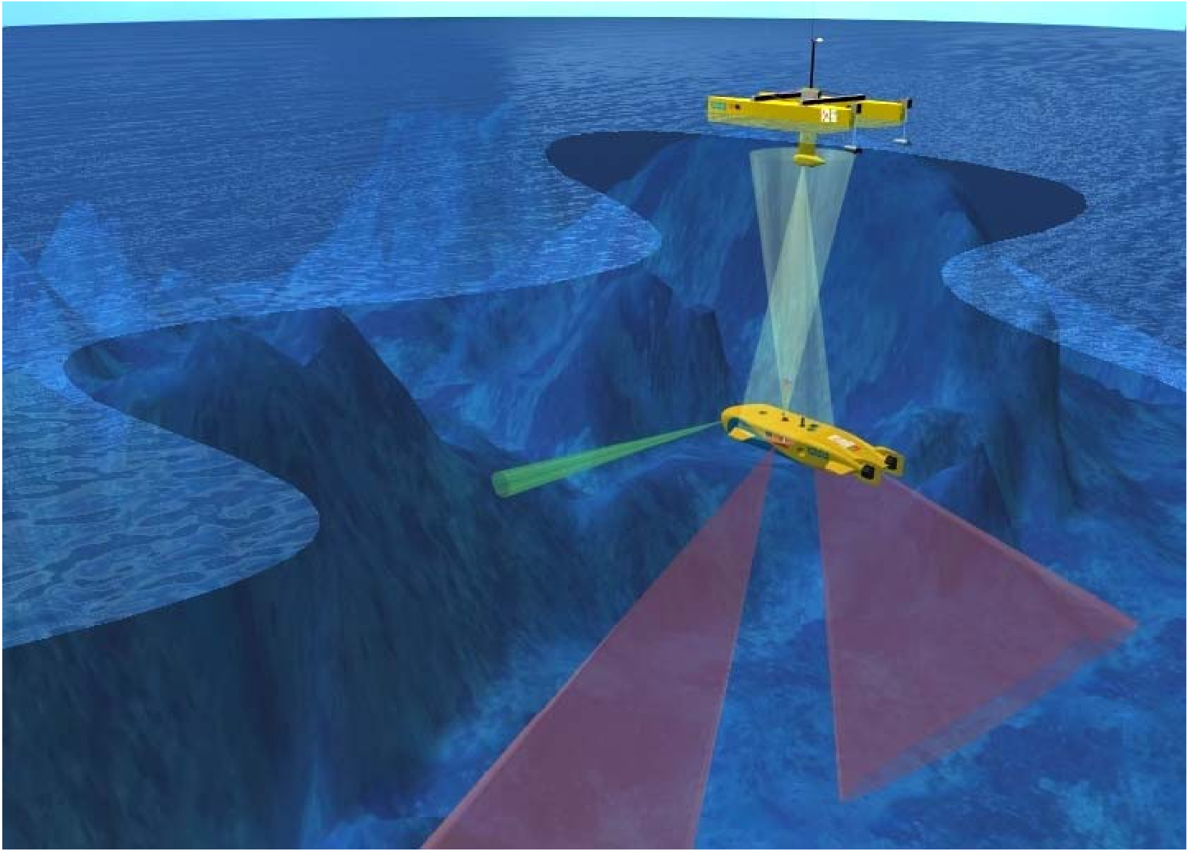
Multiple Vehicle Coordination



António M. Pascoal
António Aguiar

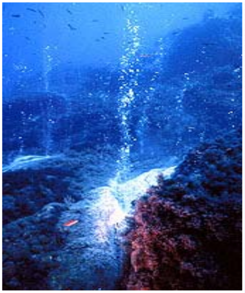
Institute for Systems
and Robotics (ISR)
IST, Lisbon, Portugal

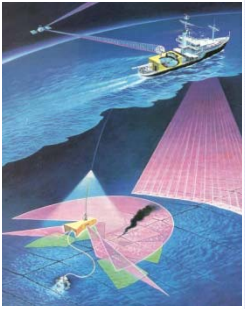
IFAC Workshop, July 6, 2008

Multiple Vehicle Coordination

Presentation based on joint work with

Almeida, João	IST/ISR, PT
Ghabchelloo, Reza	IST/ISR, PT
Hespanha, João	UCSB, USA
Hovakimyan, Naira	VPI, USA
Kaminer, Isaac	NPS, USA
Silvestre, Carlos	IST/ISR, PT
Vanni, Francesco	IST/ISR, PT





Summary:

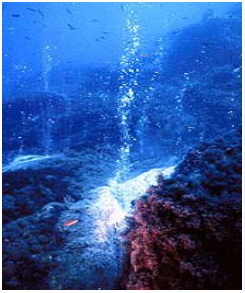
Ocean exploration: scientific challenges

The need for marine robots: technical challenges

Theory and Practice: single and multiple vehicle control

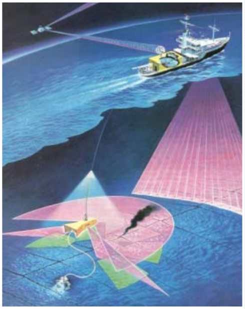
Single and Multiple Vehicle Control

Path Following



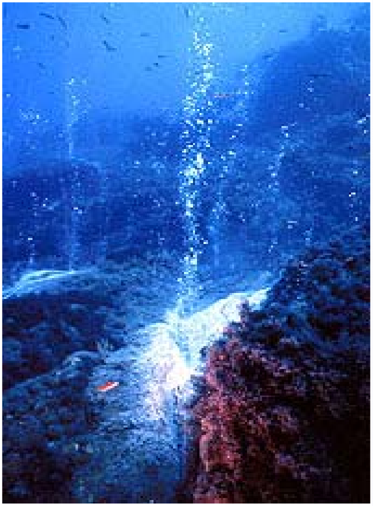
Coordinated Path Following

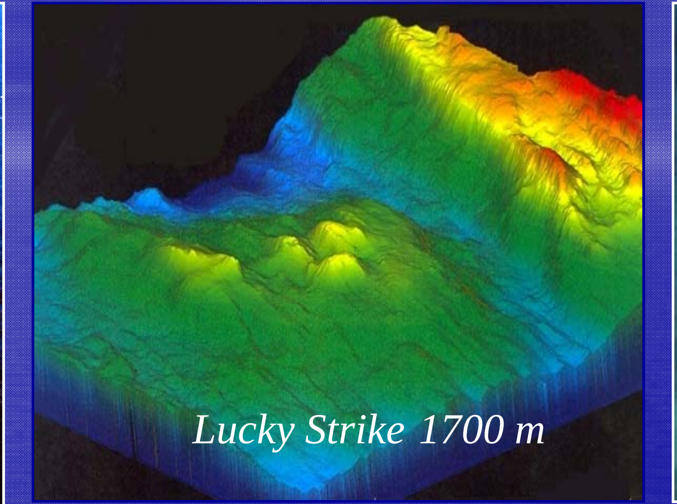
- Underactuated vehicles
- Switching communication topologies

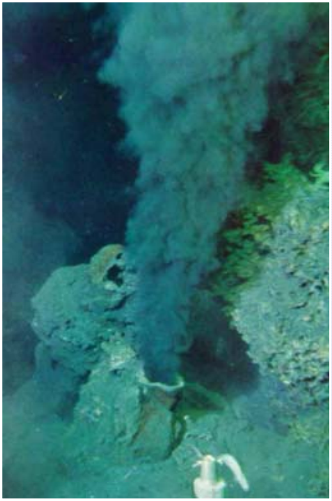


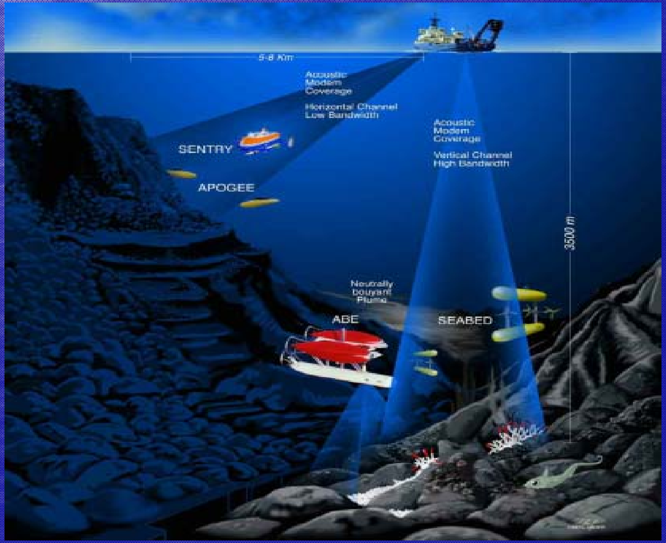
Coordination with Logic-based Communications

Sea: the Ultimate Frontier









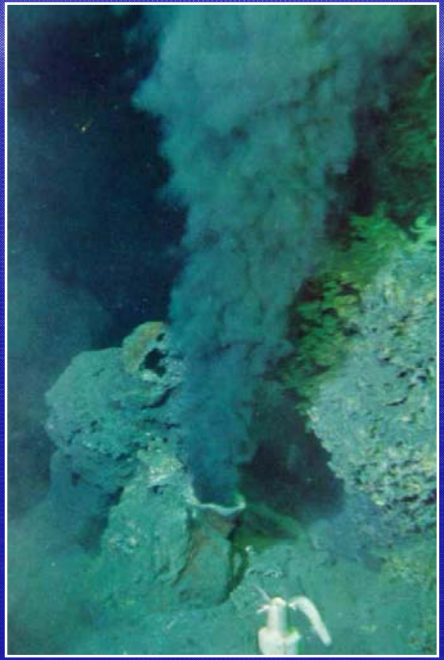
Explore the Ocean

Advanced technology is mandatory

Future: Networked Mobile/Fixed Sensors

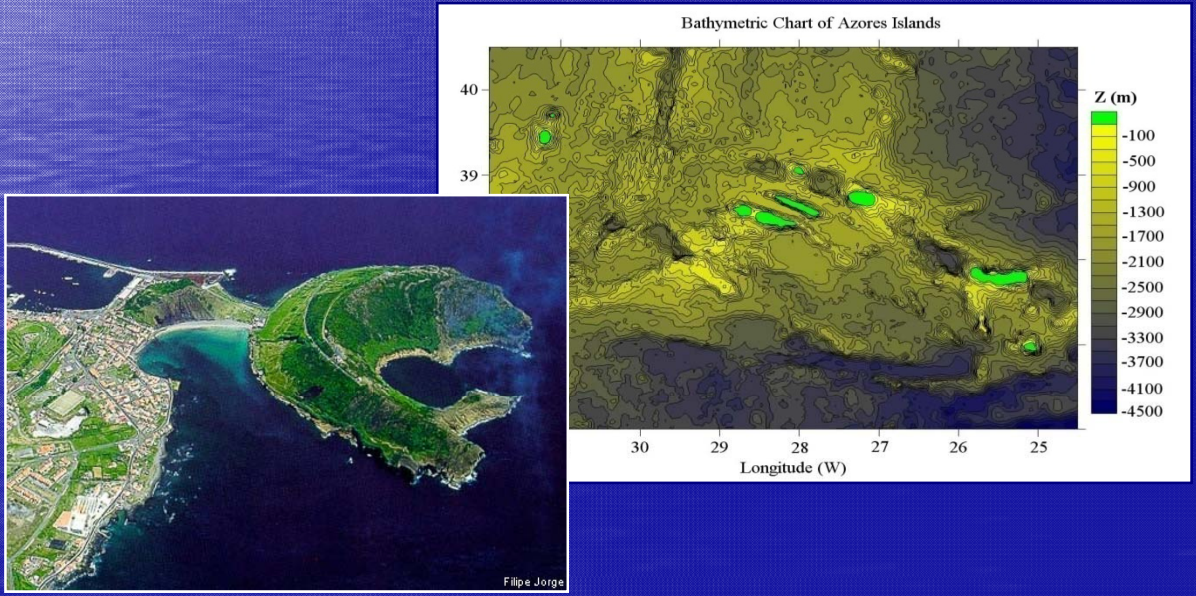
Marine data acquisition

Adequate 3-D
temporal and spatial sampling



Deep ocean

Open sea



Coastal areas

“Classical” Methods

Divers

Divers - restricted coverage; dangerous.
Hard to georeference data.

“Classical” Methods

Research Vessels

Vessels (tool par excellence) -

Poor maneuverability; poor 3-D + time coverage.

High operation costs.

“Semi-Classical ” Methods

Manned Submersibles (direct observation of the deep sea)

Nautile, IFREMER, FR

LULA, Rebikoff Foundation,

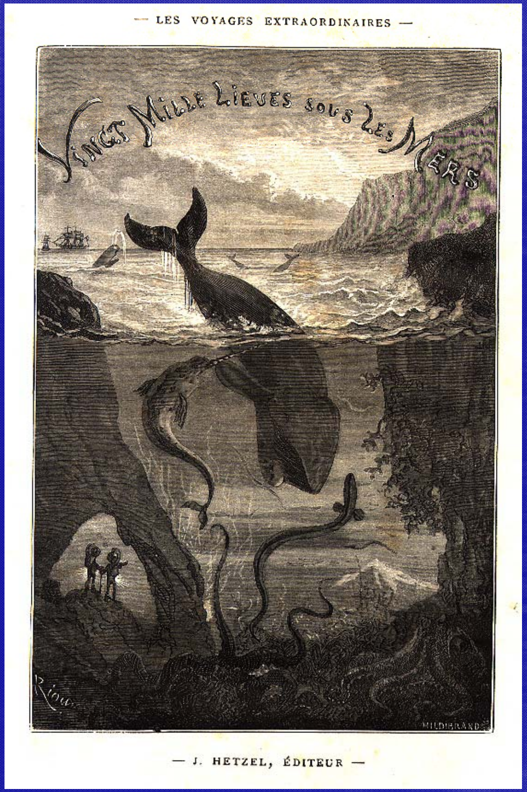
Azores, PT

“Semi-Classical ” Methods

LE FLEUVE NOIR. 97

Le capitaine Nemo prit la hauteur du soleil. (Page 99.)

Glimpses of amazing undersea adventures



— LES VOYAGES EXTRAORDINAIRES —

VINGT MILLE LIEUES SOUS LES MERS

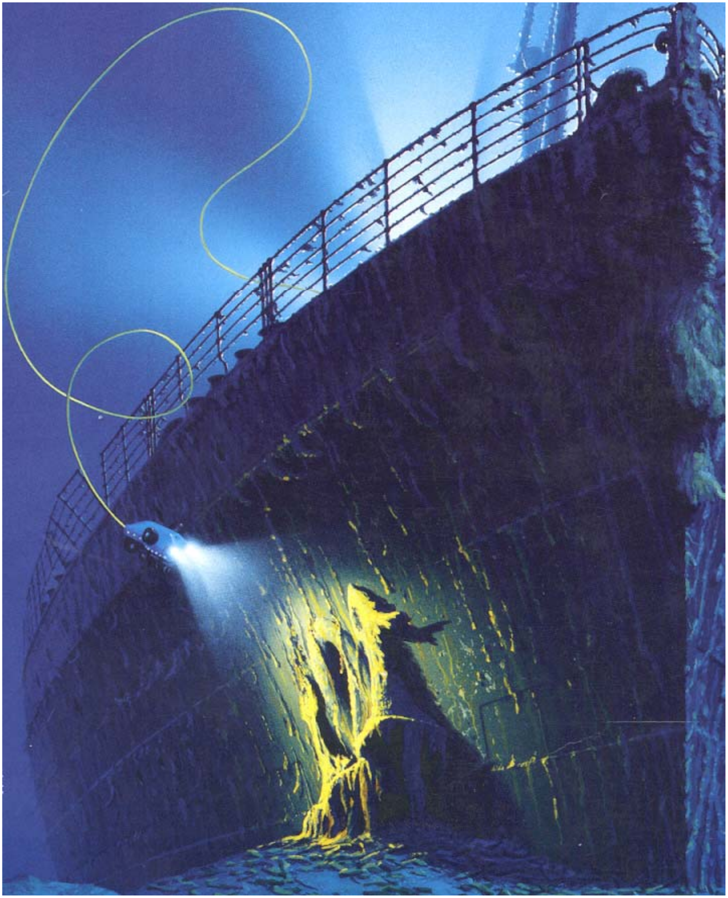
— J. HETZEL, ÉDITEUR —

Limited ocean coverage

Jeopardize human lives

High operation costs

"Modern" Methods



ROVs – Remotely Operated Vehicles

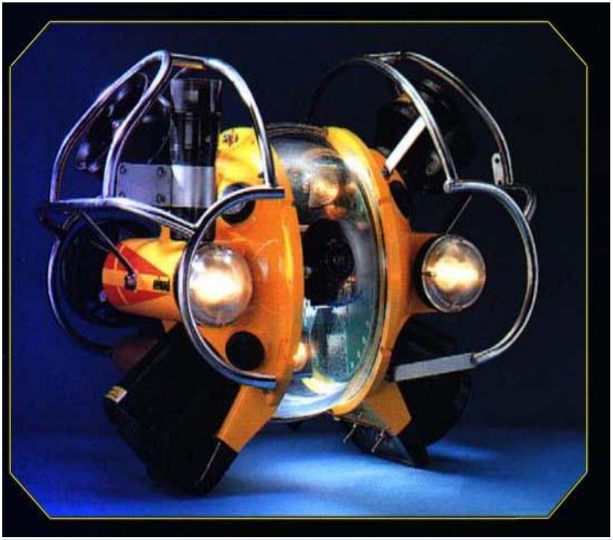
TITANIC

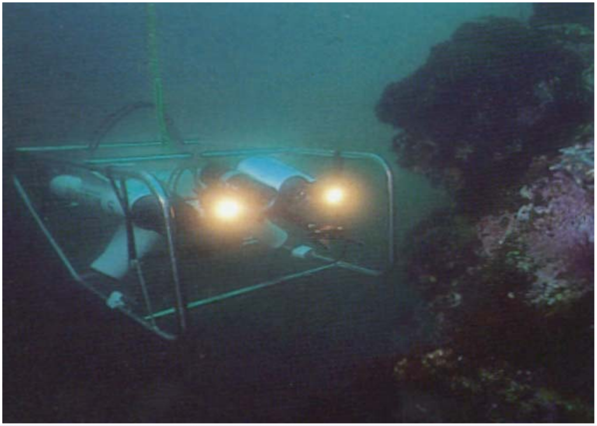
The small companion ROV

(carrying an umbilical)

"Modern" Methods

ROVs – Remotely Operated Vehicles





Present trend:

To free the end-user from the tedious task of direct vehicle operation.

“Modern” Methods

AUVs - Autonomous Underwater Vehicles (cut the umbilical!)

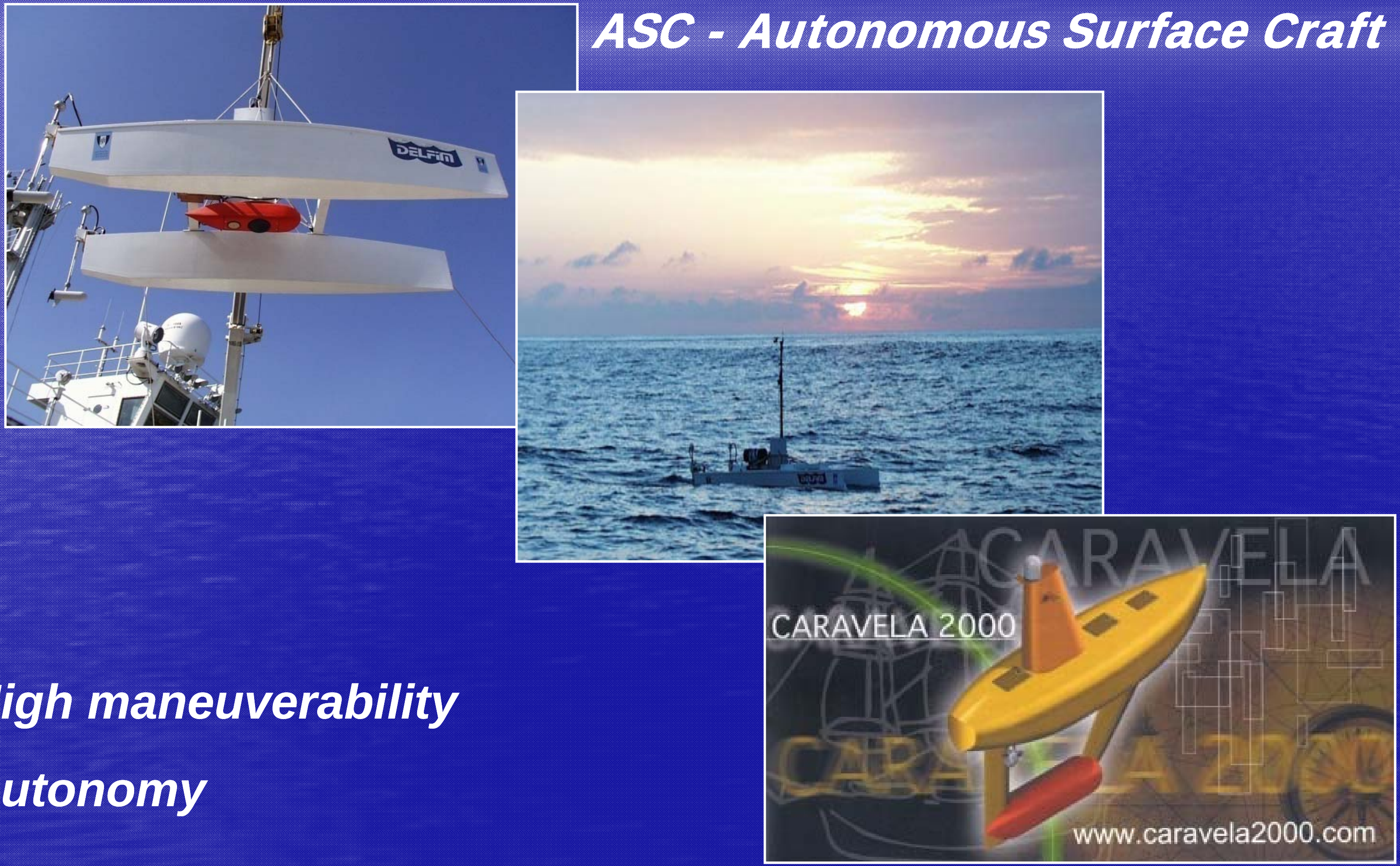
High maneuverability

Autonomy

Automatic execution of tedious tasks

“Modern” Methods

ASC - Autonomous Surface Craft



High maneuverability

Autonomy

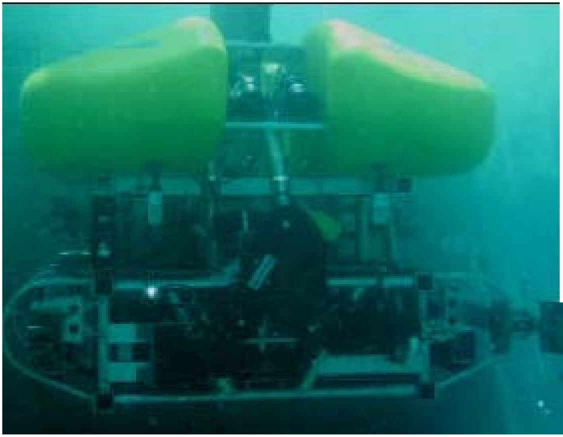
“Modern” Methods

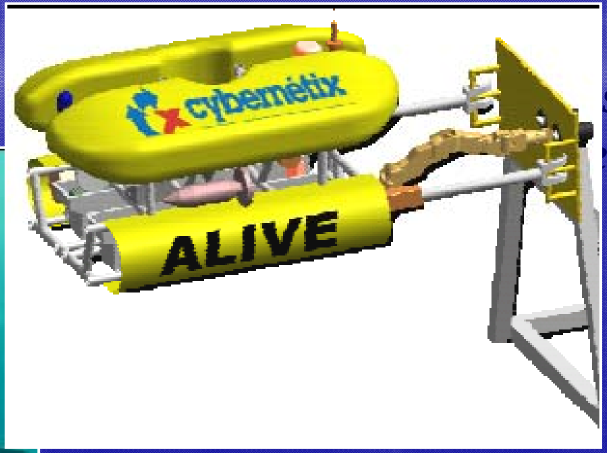
Freesub

Network, EC

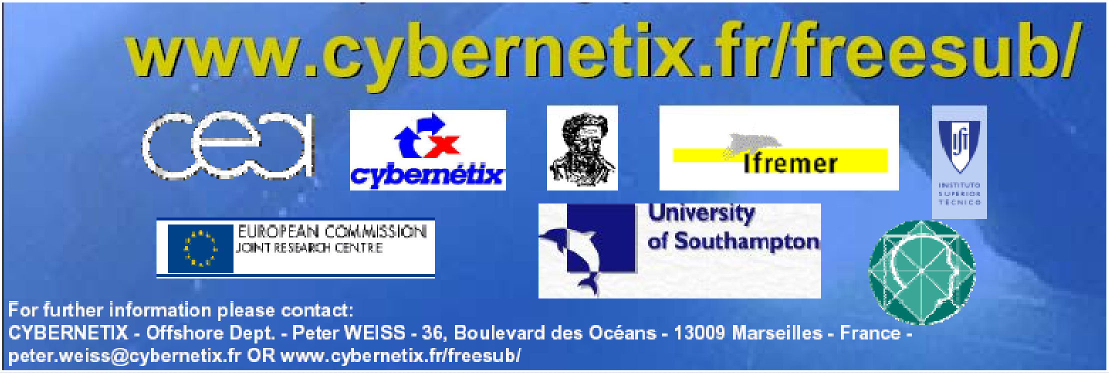
ALIVE (FR)

2 back thrusters





Intervention AUVs



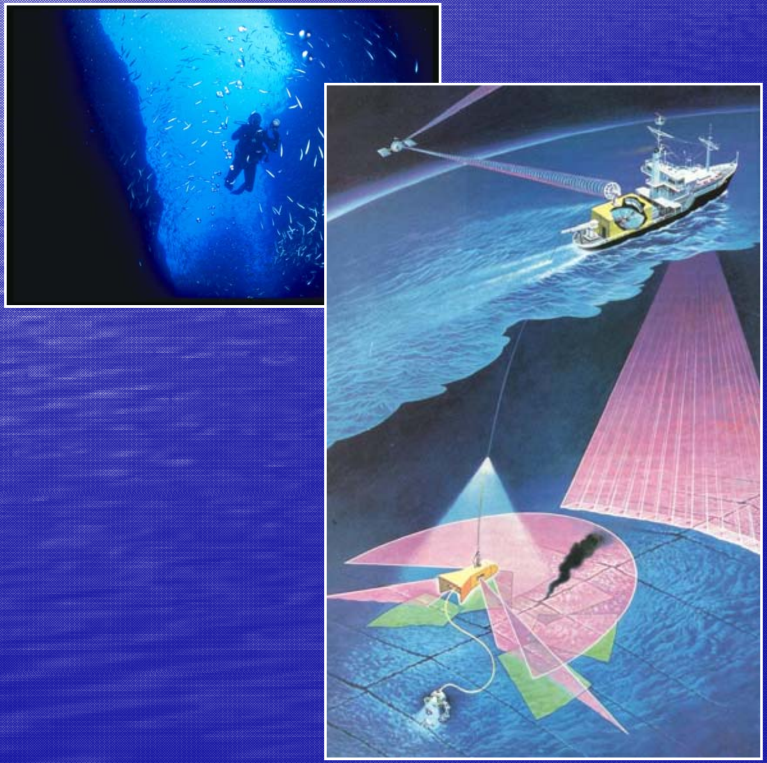
www.cybernetix.fr/freesub/

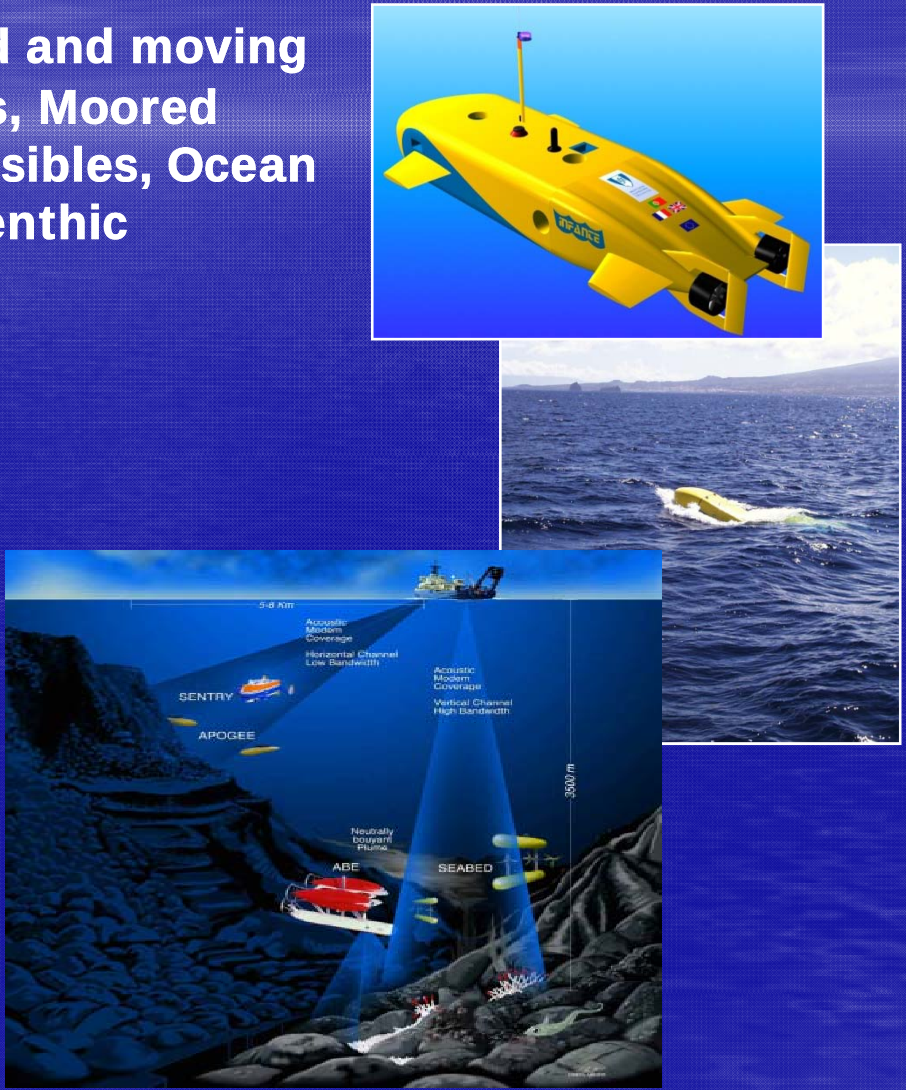
For further information please contact:
CYBERNETIX - Offshore Dept. - Peter WEISS - 36, Boulevard des Océans - 13009 Marseilles - France -
peter.weiss@cybernetix.fr OR www.cybernetix.fr/freesub/

AUV-like (no umbilical)
Bluff body
Hovering / Intervention capabilities

“Future” Trends

Sampling networks – fixed and moving units (Divers, Floating devices, Moored equipment, Inhabited submersibles, Ocean vessels, ROVs, AUVs, ASCs, Benthic stations).



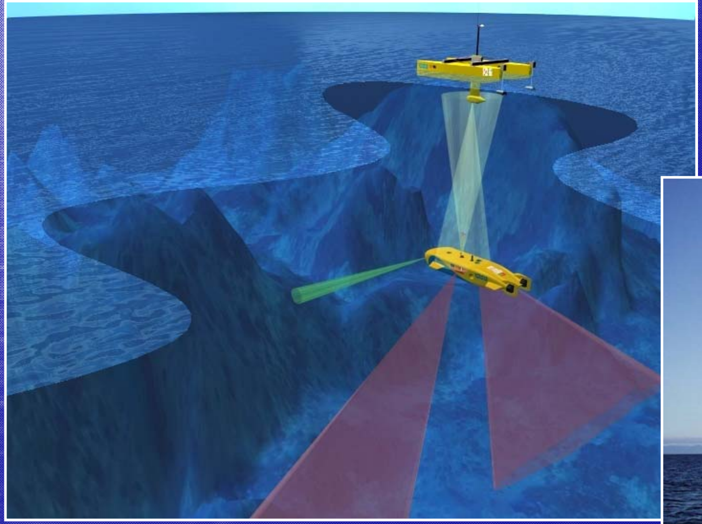


Sampling Networks

Key Issues: Communications, Information, Decision, Control.

Stepping stones:

Single and coordinated vehicle control



The ASIMOV concept

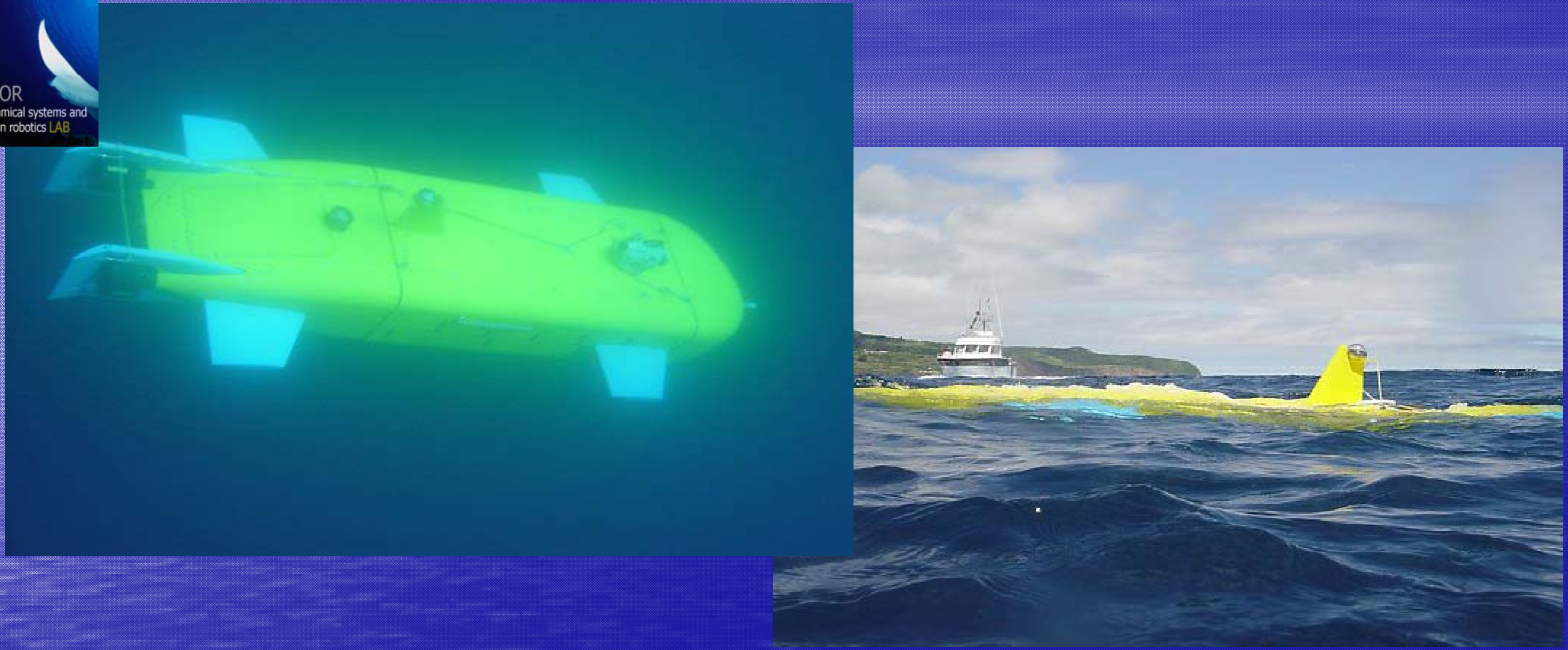
MAST-III, EC

MONAZ, PT-USA

Office of Naval Research

Control Problems (AUVs)

DSOR
dynamical systems and
ocean robotics LAB



Speed, Heading, and Depth Control

Bottom Following (Terrain Contouring)

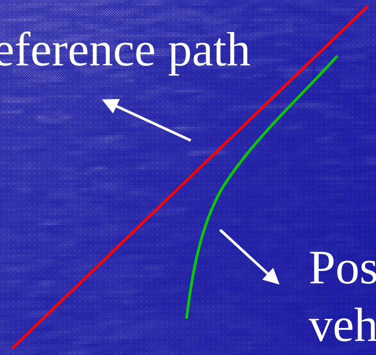
Trajectory Tracking and Path Following

Control at very low depth (under the influence of sea waves)

A word about T Tracking and P Following

Path following

- Reference path given in a time-free parameterization
- Constant forward velocity
- ‘Smoother’ convergence to the path



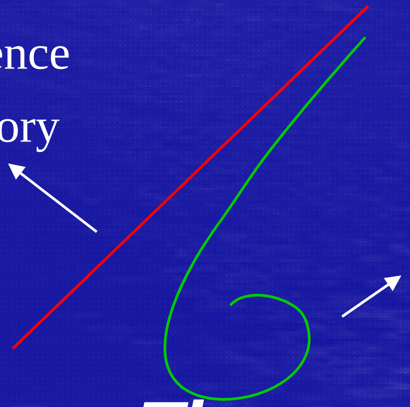
Reference path

Possible vehicle trajectory

Space

Trajectory Tracking

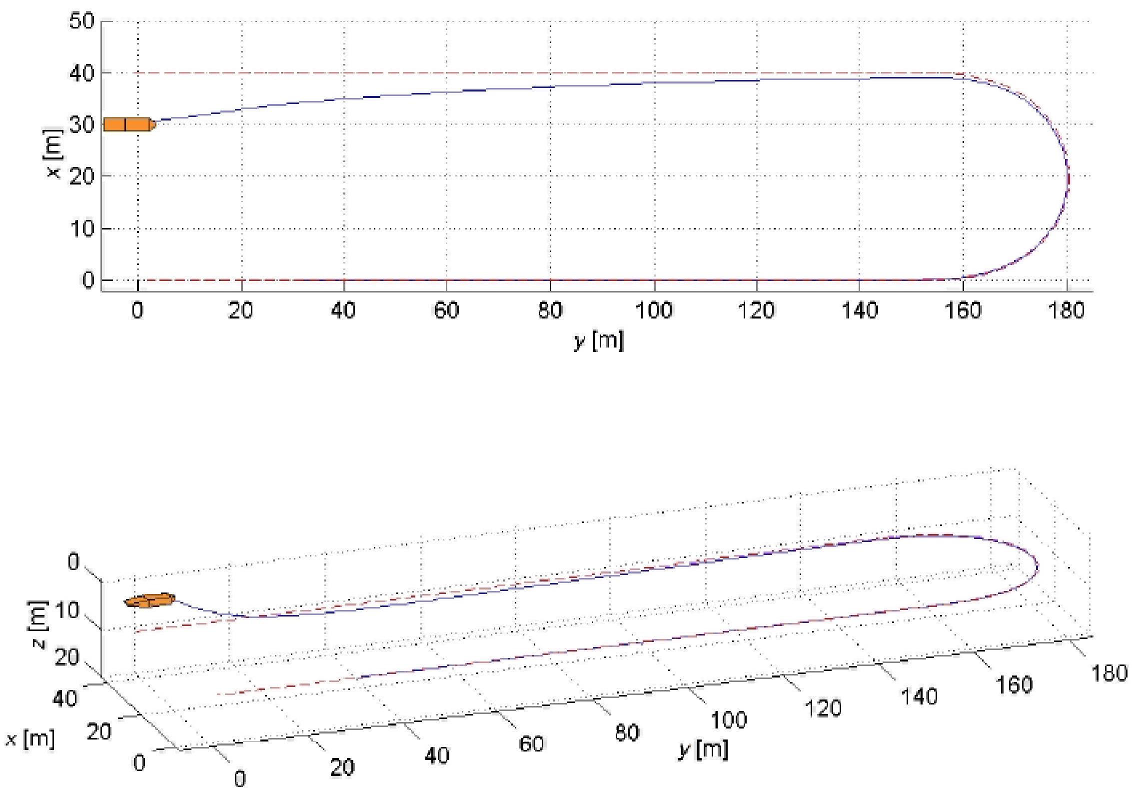
- Time and space reference trajectory
- The vehicle may turn back in its attempt to be at a given reference point at a prescribed time



Reference trajectory

Space x Time

AUV-Path Following



AUV Path Following in the presence

of an unknown ocean current ("flying crab")

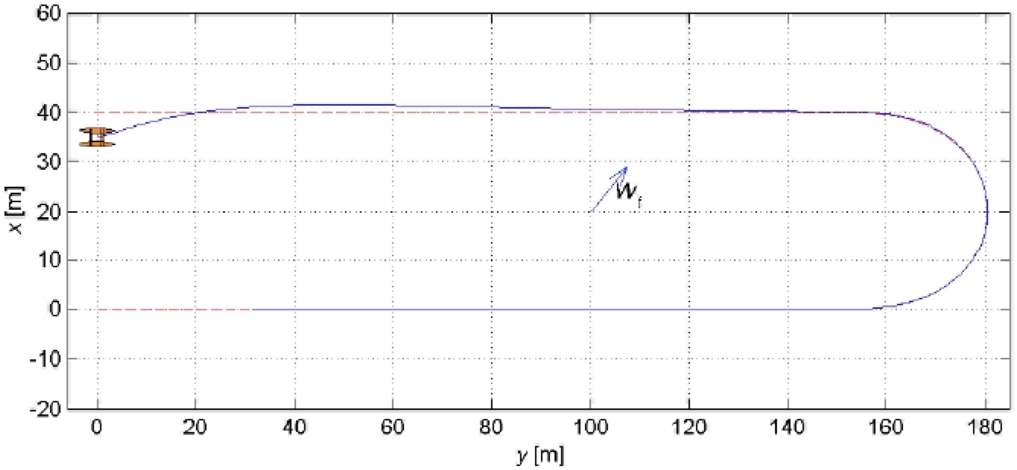
Control Problems (ASC)

Speed and Heading Control

Trajectory Tracking and Path Following

(in the presence of wind, currents, and ocean waves)

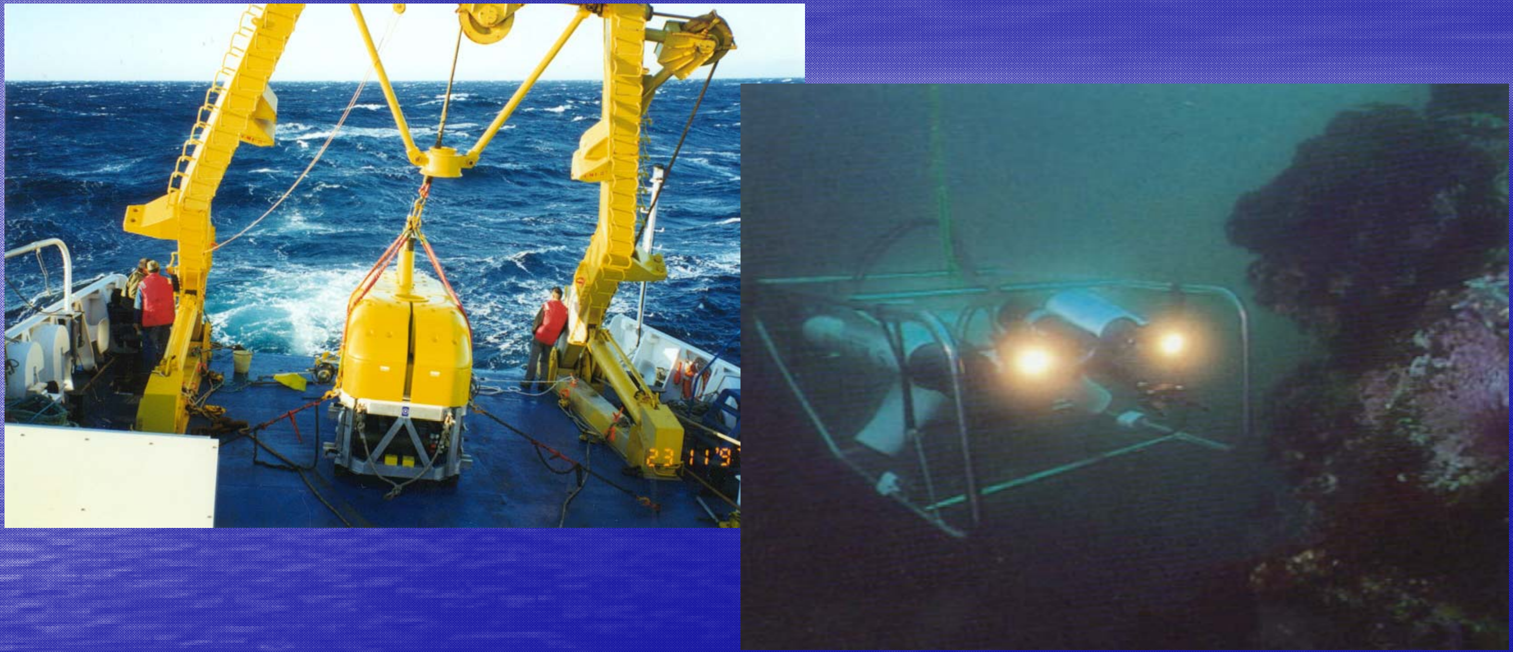
ASC-Path Following



ASC Path Following in the presence

of an unknown ocean current ("flying crab")

Control Problems
(ROVs and “ROV-like” AUVs)



Speed, Heading, and Depth Control

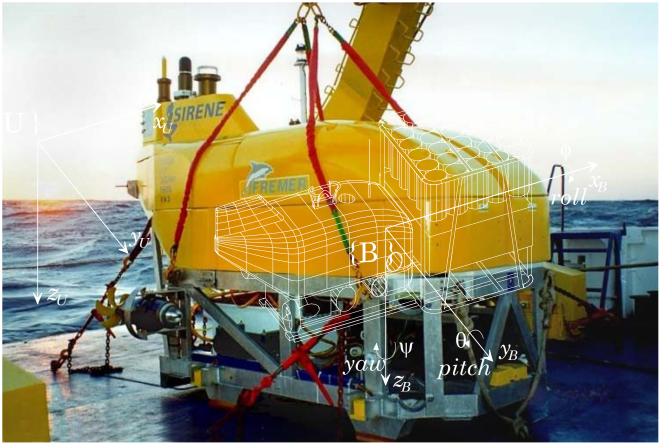
Bottom Following (Terrain Contouring)

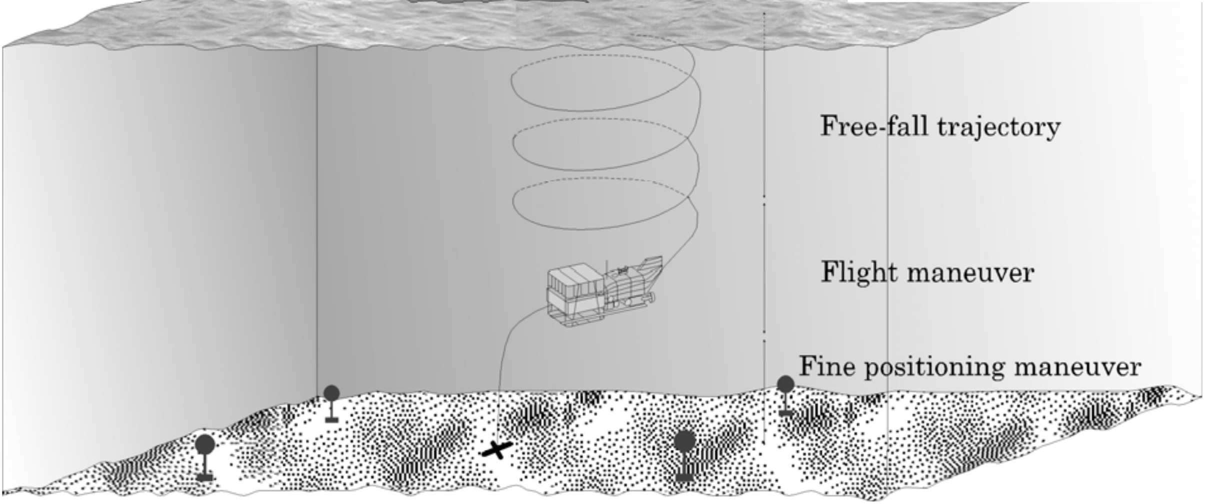
Point Stabilization and Hovering

Path Following

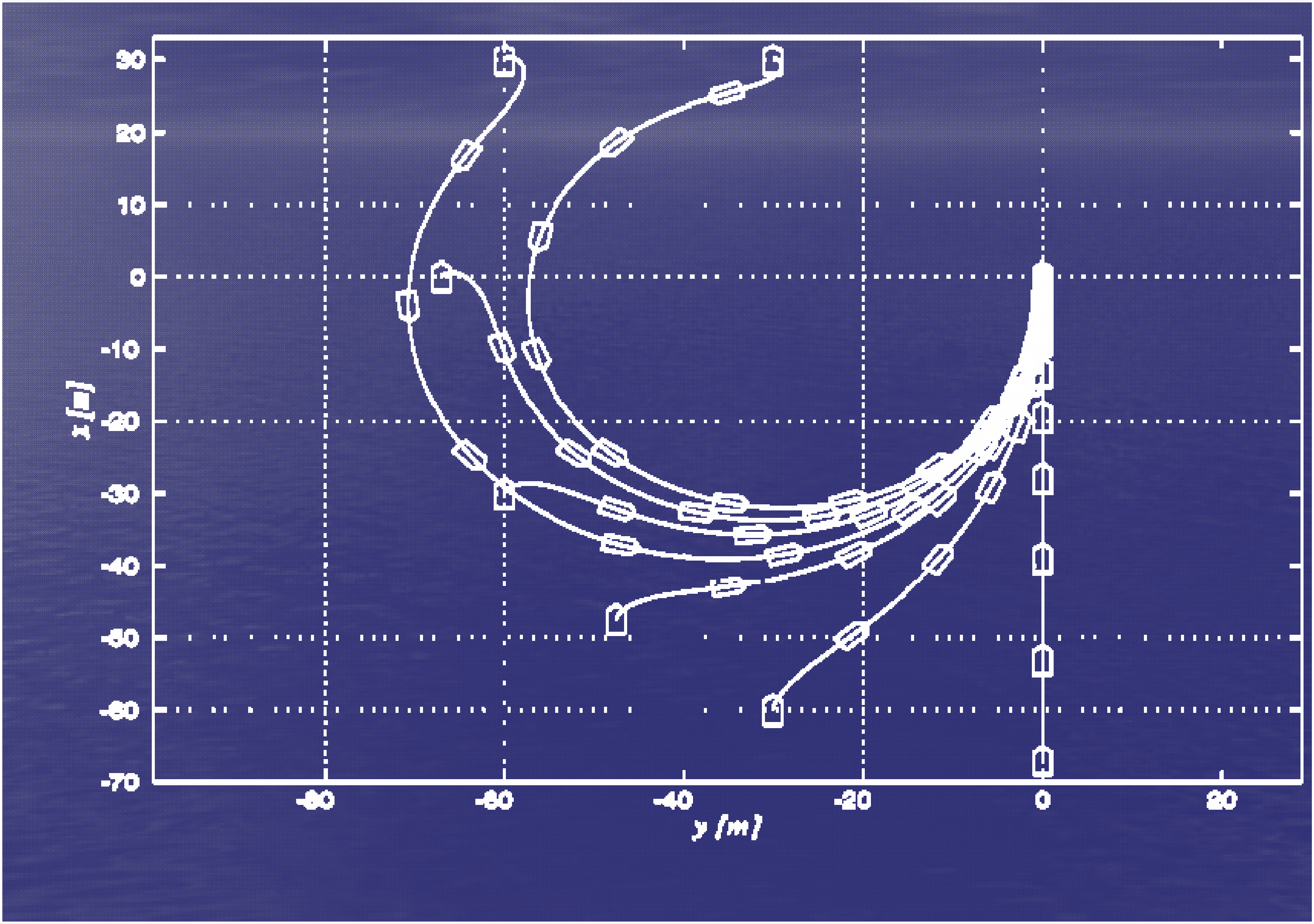
Point Stabilization

Objective: steer an underwater vehicle to a target point, with a desired orientation

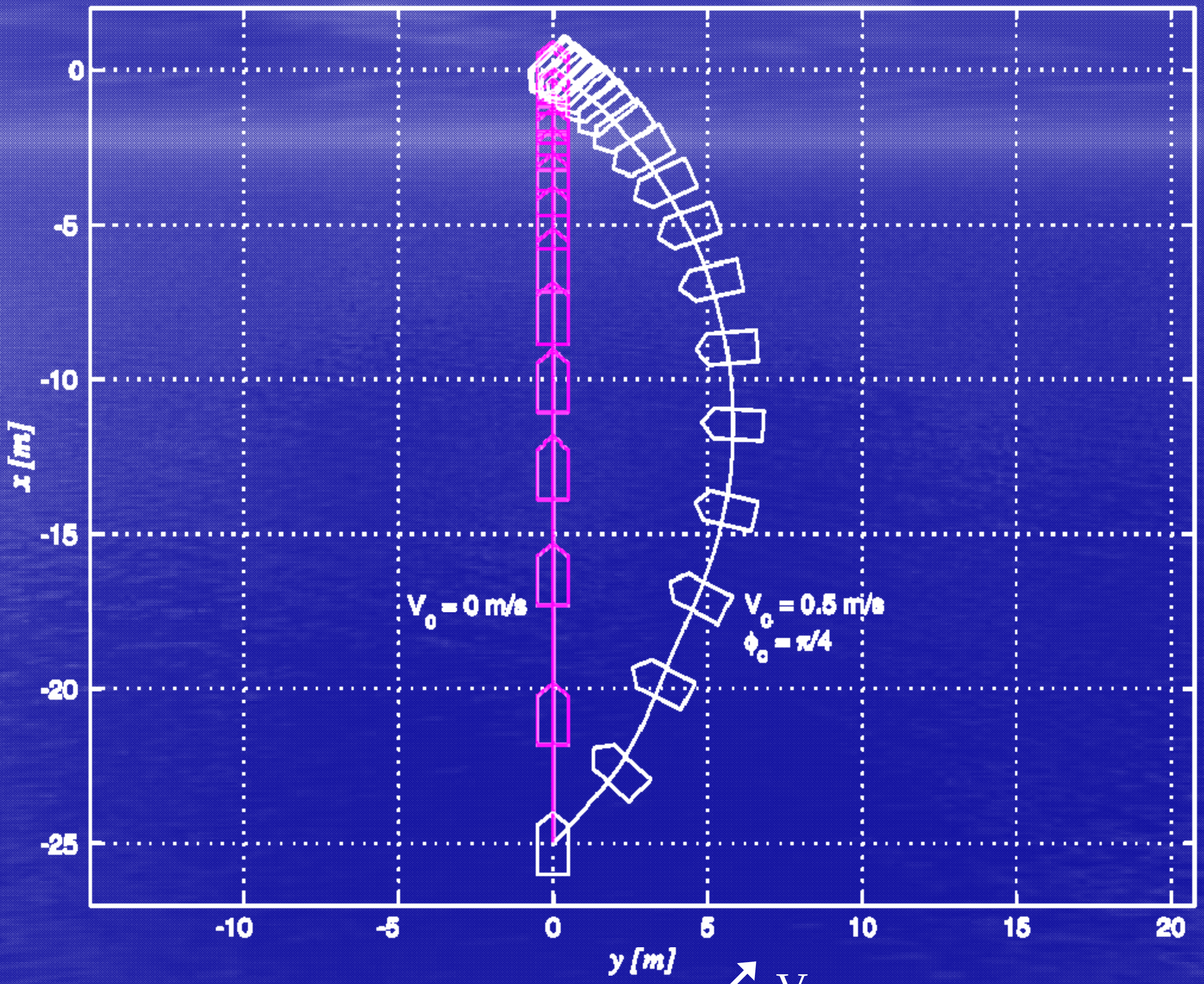




Point Stabilization

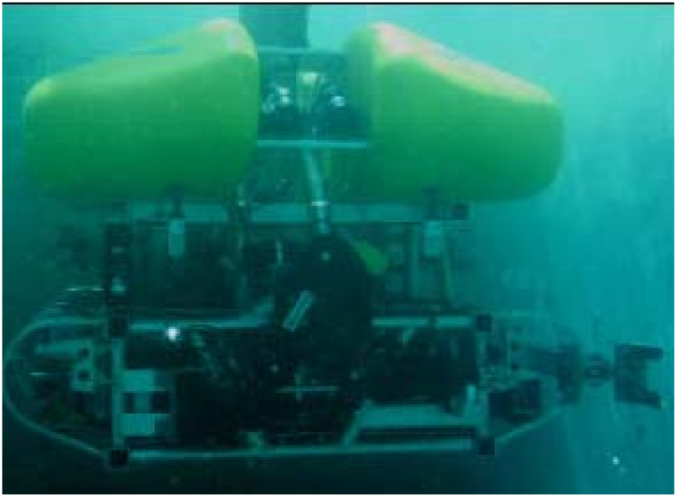


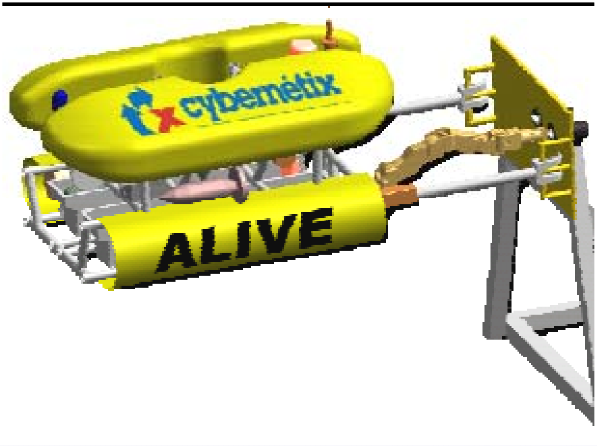
Point Stabilization with currents



V_c

Control Problems (Intervention AUVs)





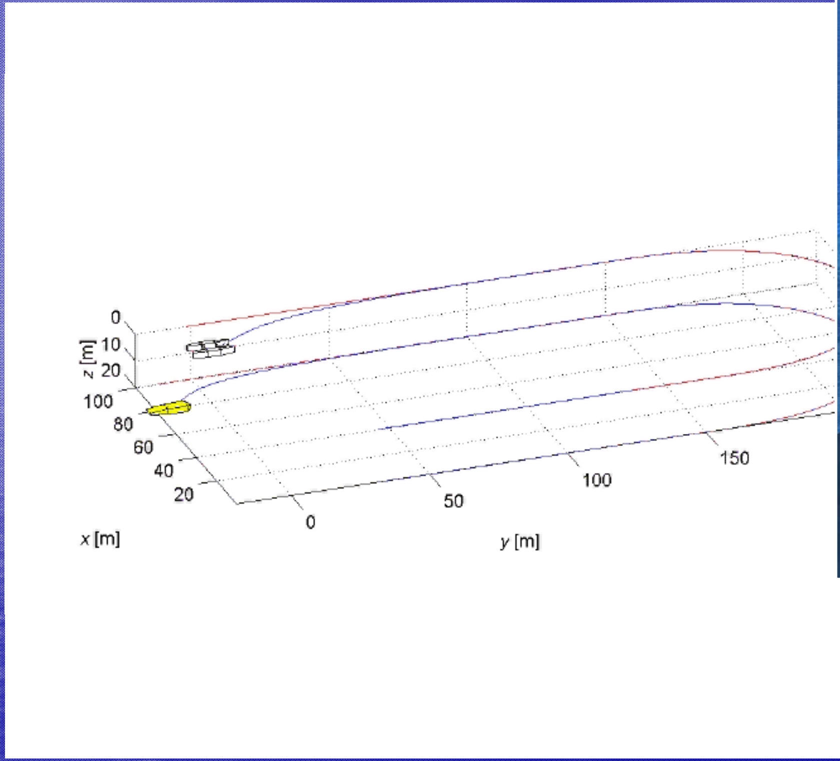
Speed, Heading, and Depth Control

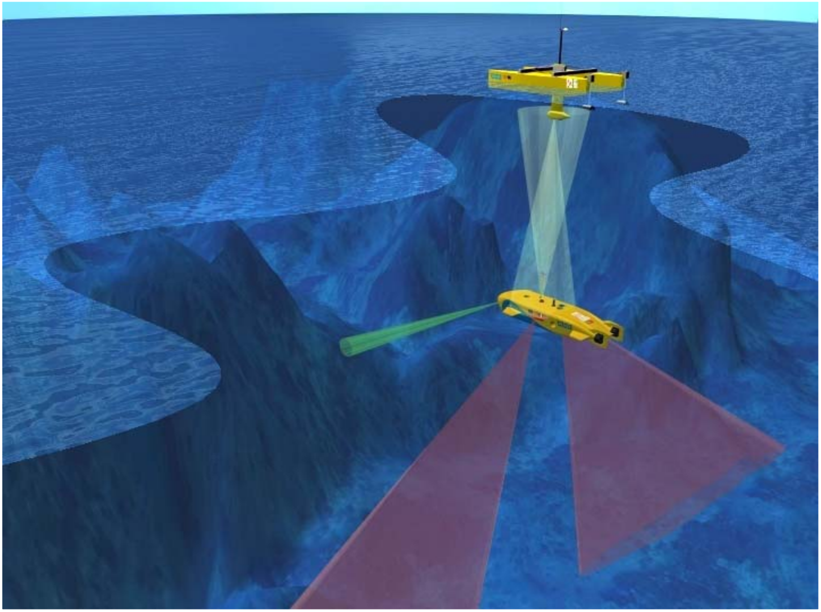
Bottom Following (Terrain Contouring)

Path Following

Point Stabilization; Hovering; Manipulation; Grasping

Coordinated Motion Control

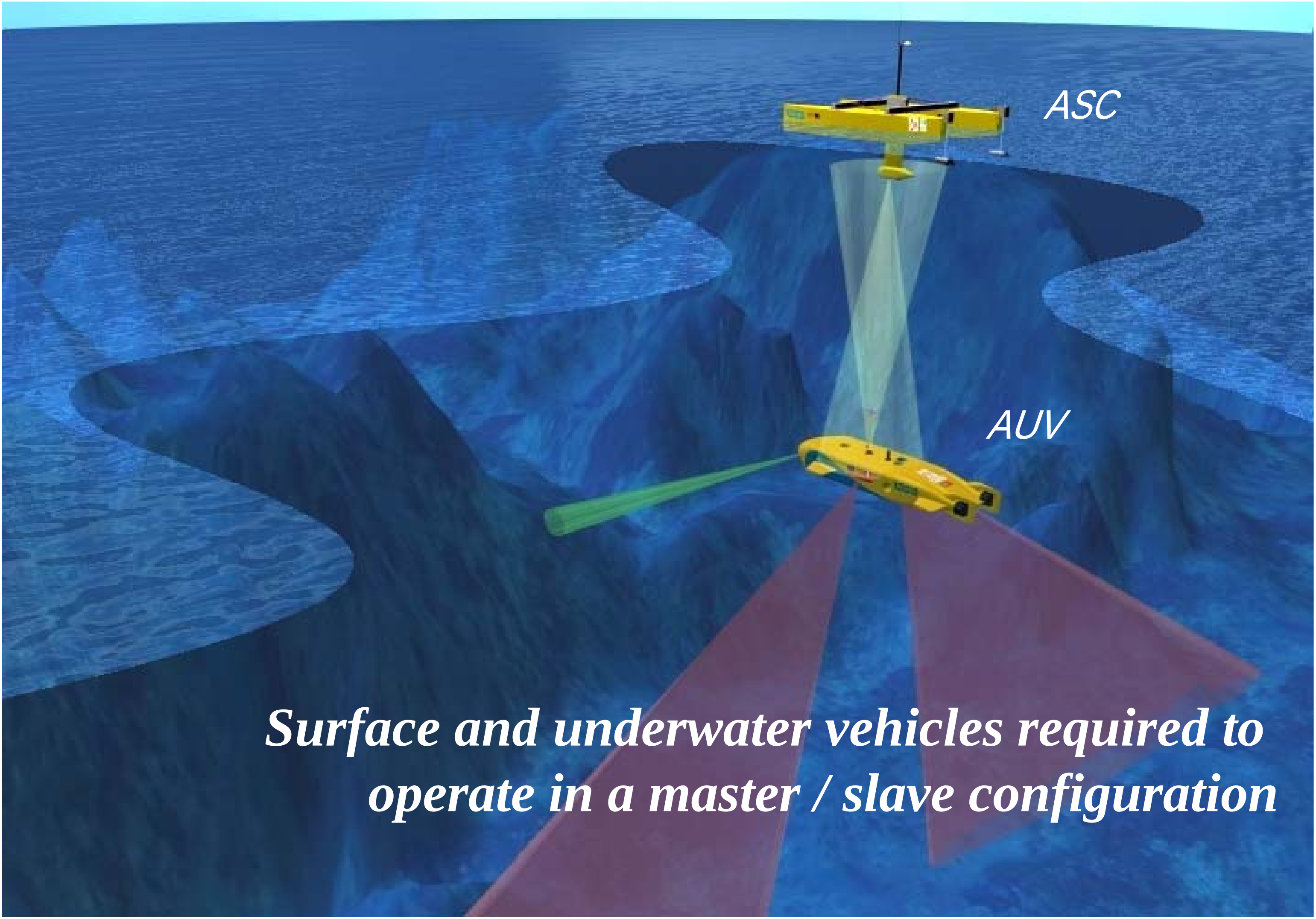




Joint Path Following while keeping inter-vehicle geometric constraints

Motion control in the presence of severe acoustic communication constraints (multipath, failures, latency, asynchronous data acquisition, reduced communication bandwidth; NETWORKED CONTROL SYSTEMS)

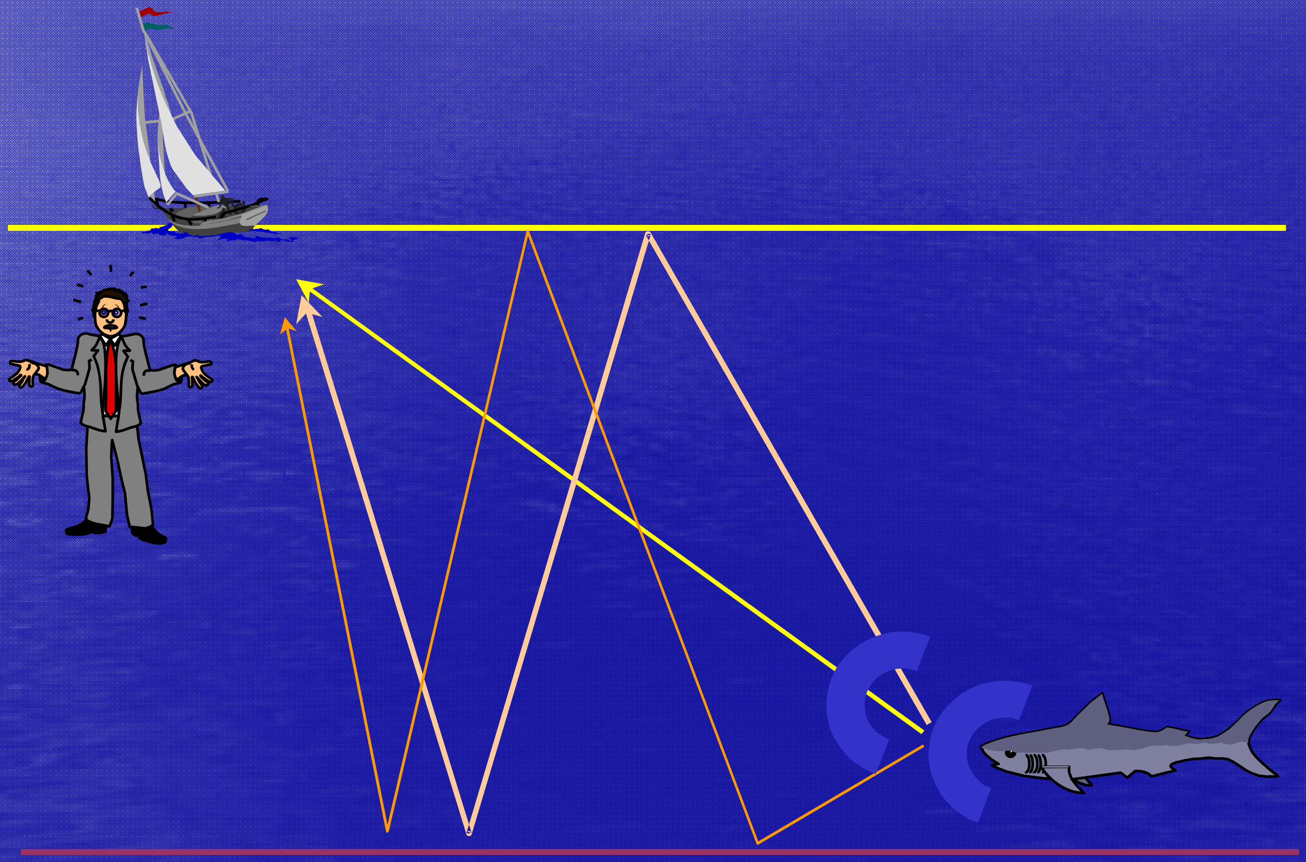
Coordinated Motion Control



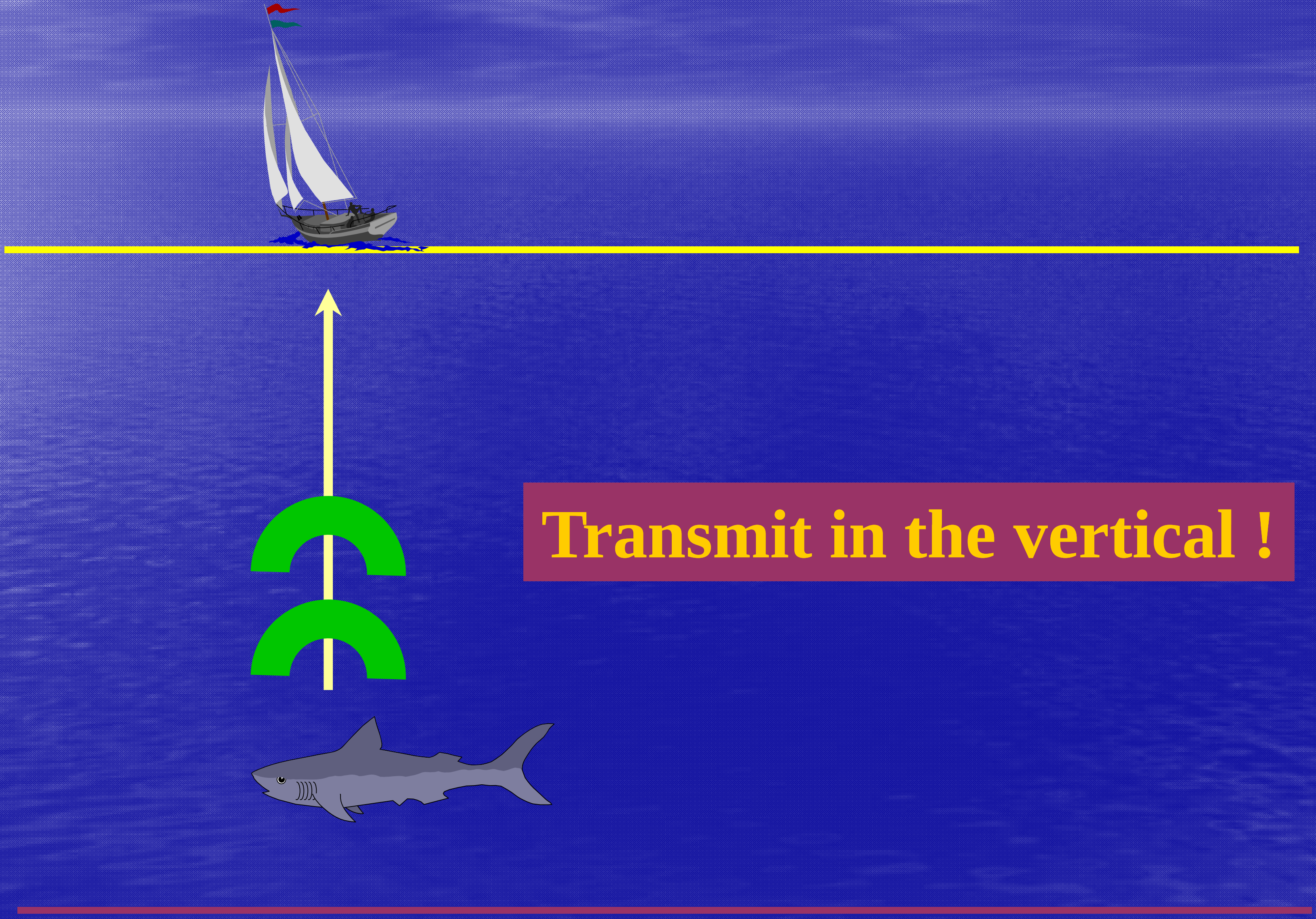
Surface and underwater vehicles required to operate in a master / slave configuration

Communications

Underwater Communications – *very hard!*



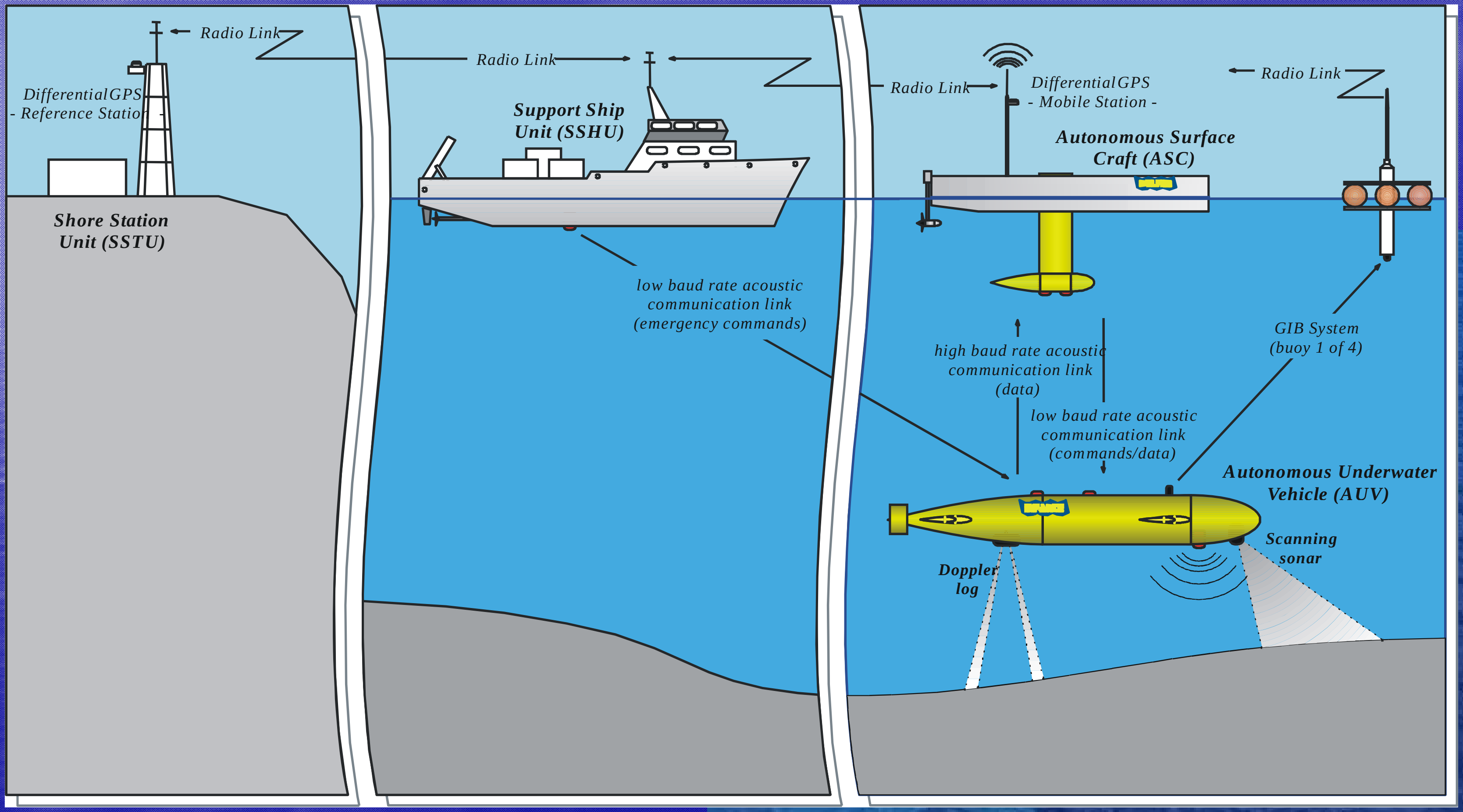
Underwater Communications



Transmit in the vertical !

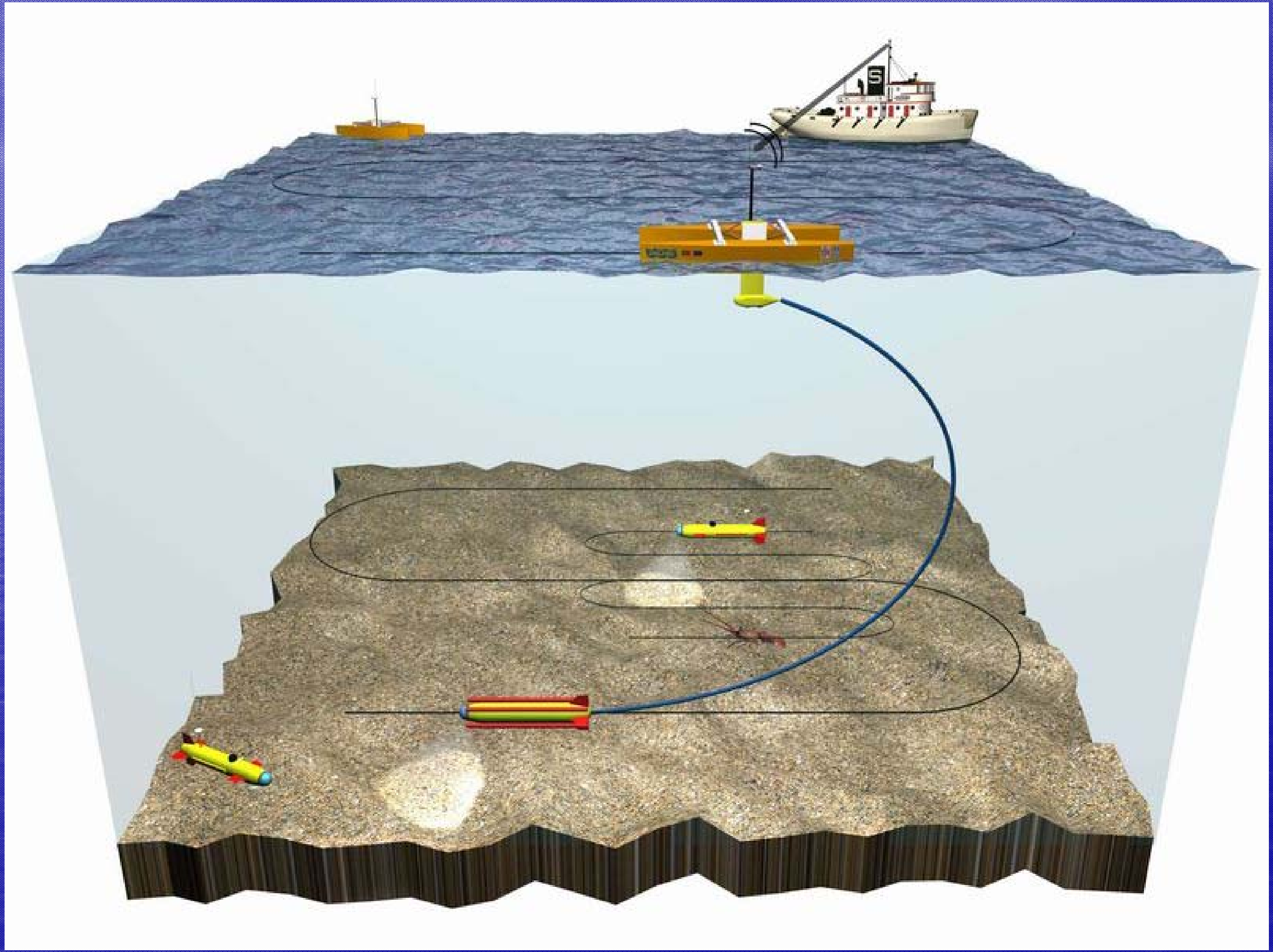
DSOR
dynamical systems and ocean robotics LAB

Coordinated Motion Control



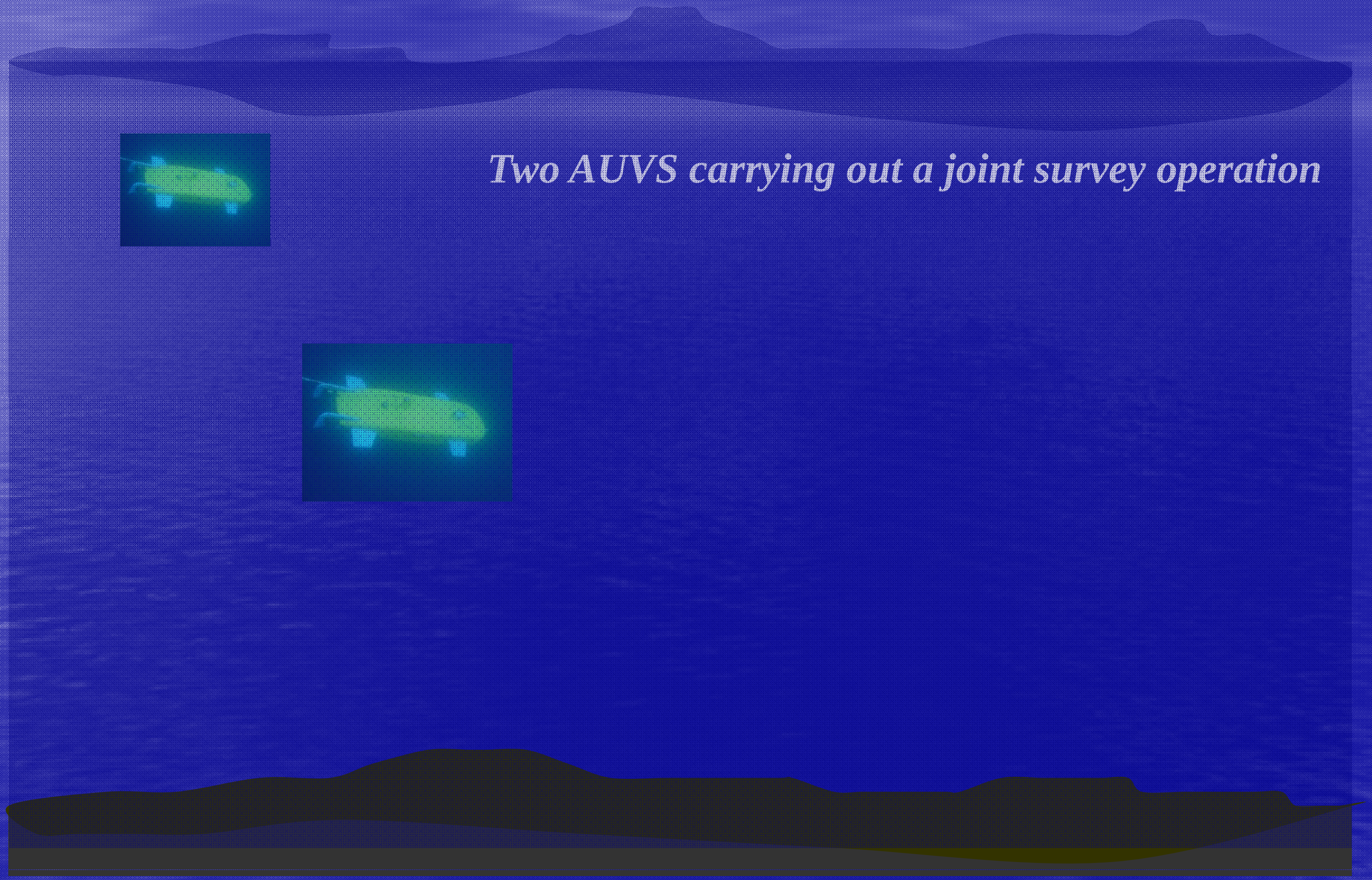
The ASIMOV concept
(project ASIMOV, EC - 2000)

Coordinated Motion Control



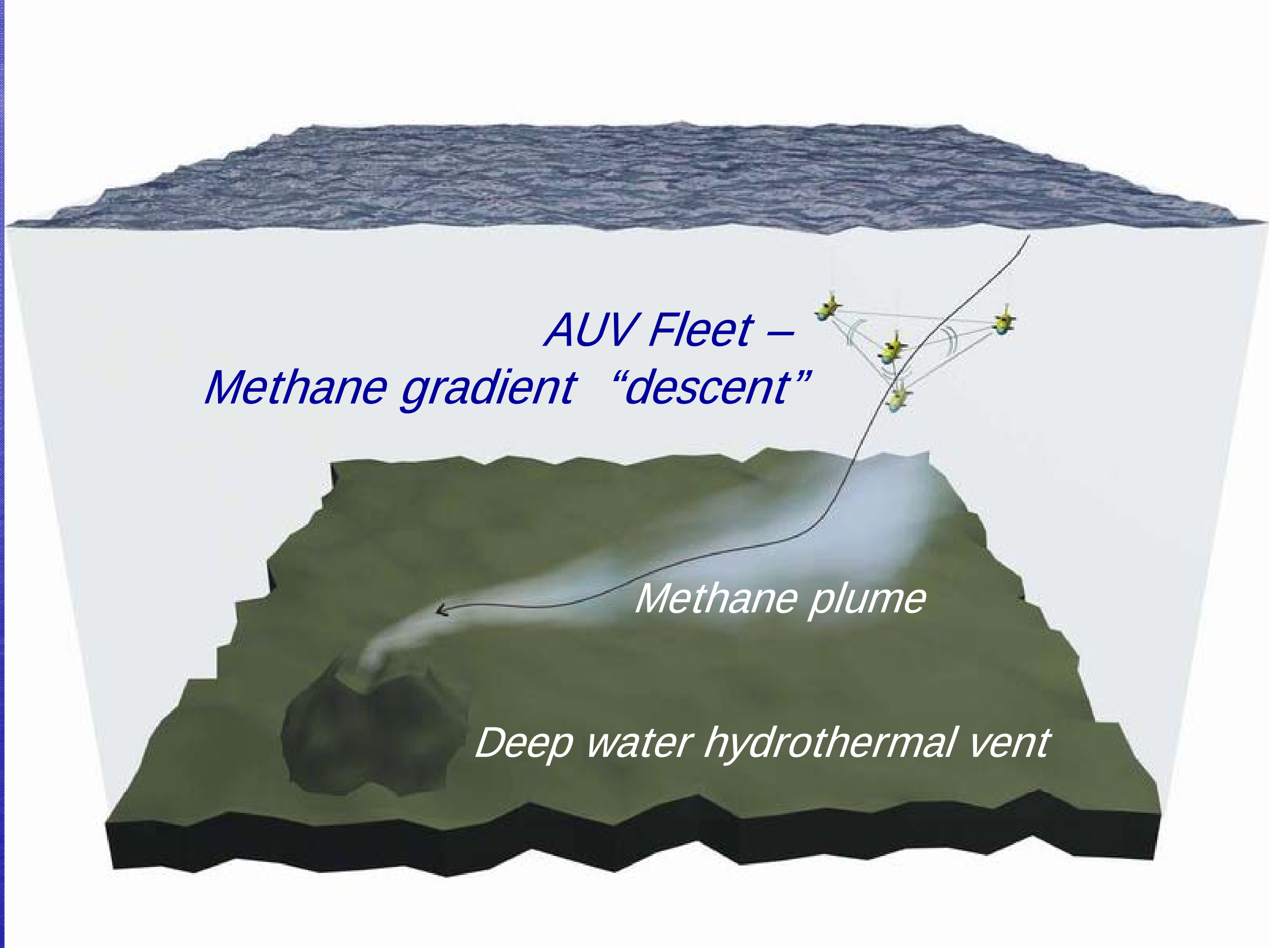
Marine Habitat Mapping using multiple vehicles (Azores)

Coordinated Motion Control



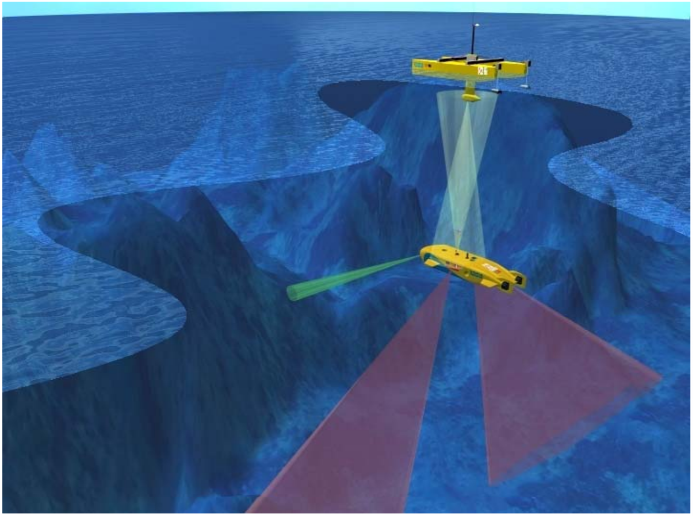
Two AUVS carrying out a joint survey operation

Coordinated Motion Control



The quest for mid-water column hydrothermal vents, Azores, PT

How it all started at IST (1998) - ASIMOV



Dream

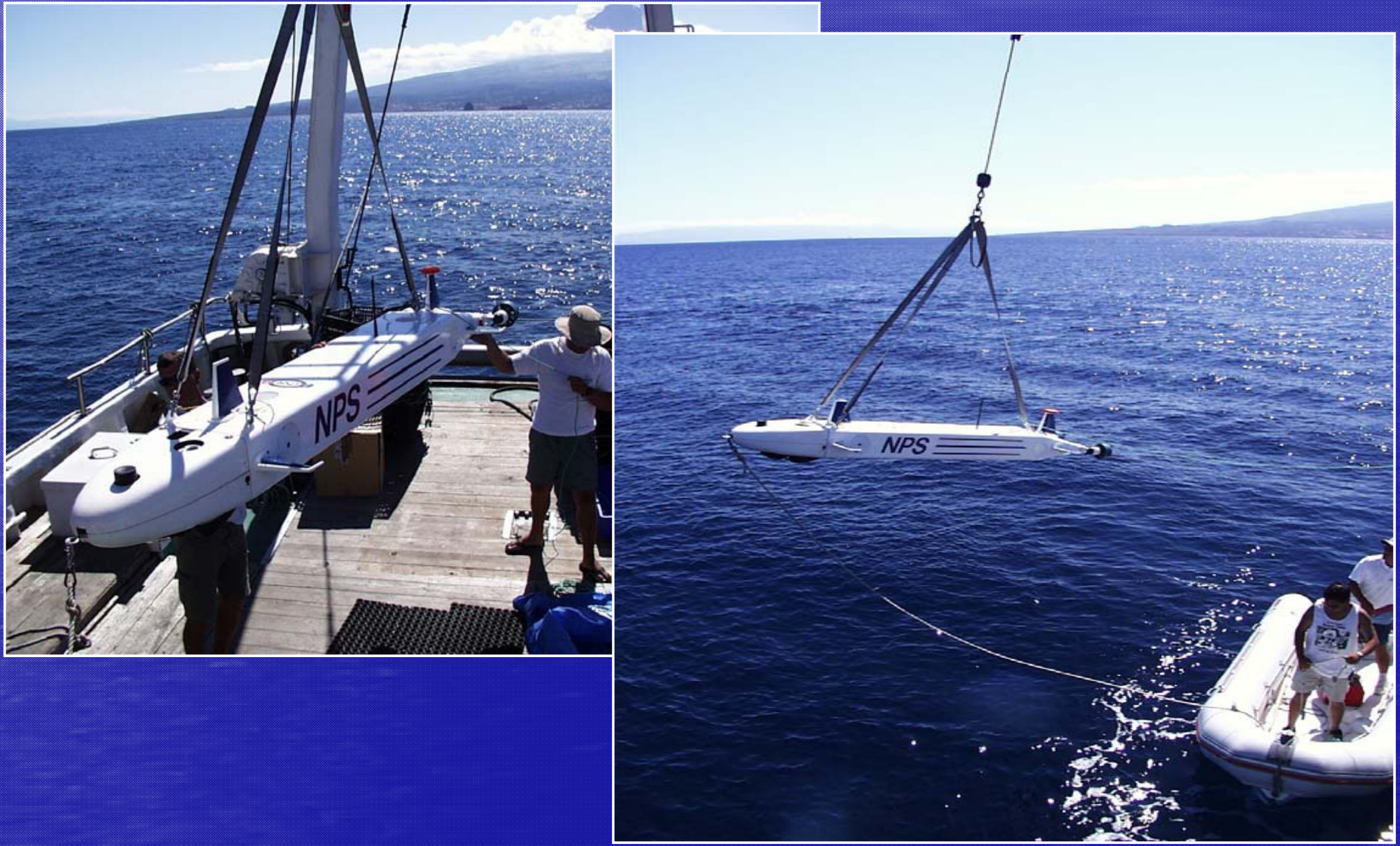
“Reality” (IST-NPS mission)

Theoretical problems: key issues

<u>Coordinated Path Following</u> while keeping inter-vehicle geometric constraints

Motion control in the presence of severe acoustic <u>communication constraints</u> (multipath, failures, latency, asynchronous comms, reduced bandwidth...)

Joint ISR / NPS mission in the Azores

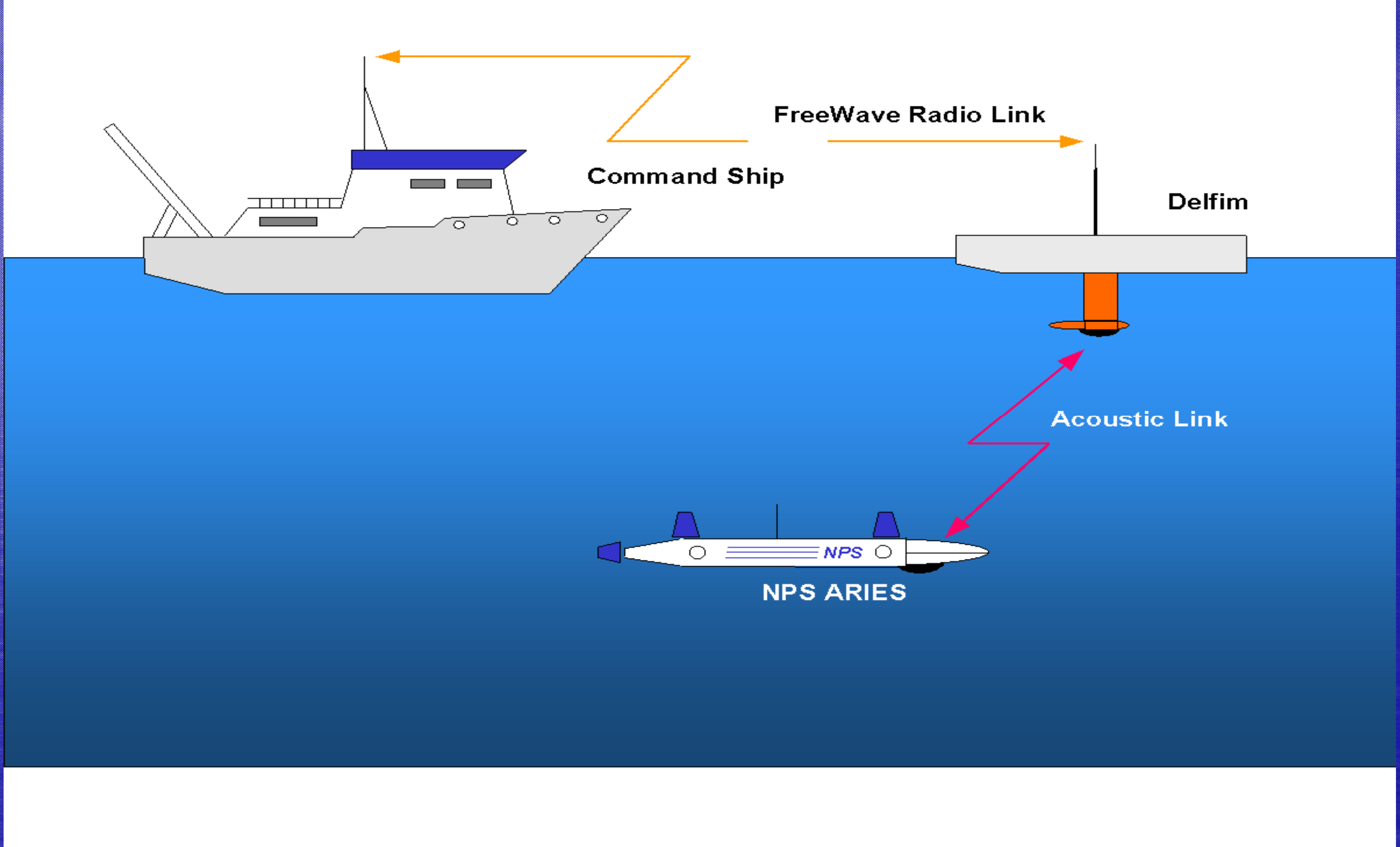


The ARIES AUV (USA) and the DELFIM ASC (PT)

Joint ISR / NPS mission in the Azores

The ARIES AUV (USA) and the
DELFIM ASC (PT)
exchanging data over an
acoustic link

Joint ISR / NPS mission in the Azores



The ARIES AUV (USA) and the DELFIM ASC (PT) exchanging data over an acoustic modem

Joint ISR / NPS mission in the Azores

Path Following

Inspired by the work of Claude Samson et al. for wheeled robots

A. Micaelli and C. Samson (1992). Path following and time-varying feedback stabilization of a wheeled robot. In *Proc. International Conference ICARCV'92*, Singapore.

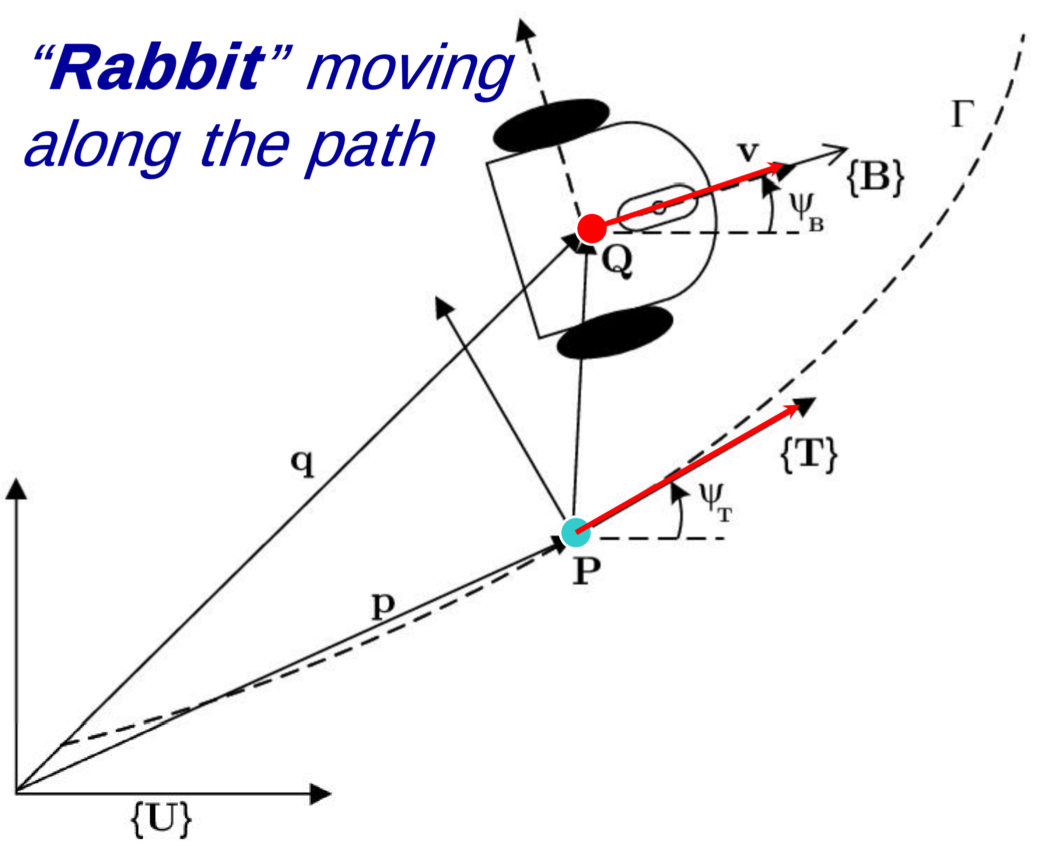
✓. Use ***forward motion*** to make the robot track a desired speed profile.

✓. Compute the ***closest point*** on the path.

✓. Compute the ***Serret-Frenet (SF)*** frame at that point.

✓. Use ***rotational motion*** to align the body-axis with the SF frame and reduce the distance to closest point to zero.

Path Following


“**Rabbit**” *moving along the path*

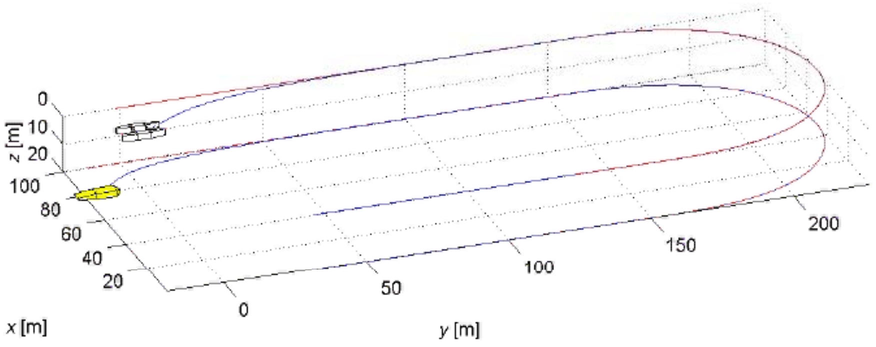
Important related work

R. Skjetne, T. I. Fossen,
P. V. Kokotovic.
Robust output maneuvering for a class of nonlinear systems. Automatica, 40(3):373—383, 2004.

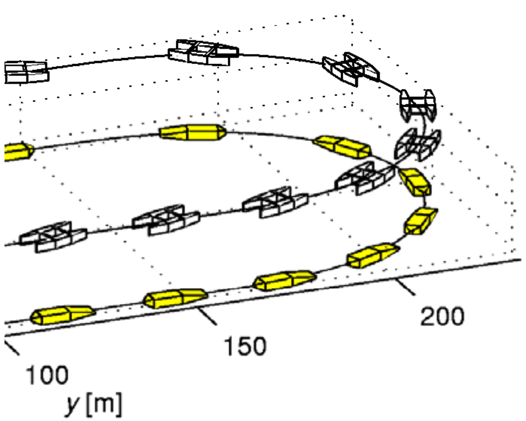
Avoiding Singularities!

“Nonlinear Path Following with Applications to the Control of Autonomous Underwater Vehicles,” L. Lapierre, D. Soetanto, and A. Pascoal, *42th IEEE Conference on Decision and Control*, Hawai, USA, Dec. 2003

Coordinated AUV / ASC behavior



ied Trajectory Tracking,
sium on the Mathematical
D, USA, June 1992)



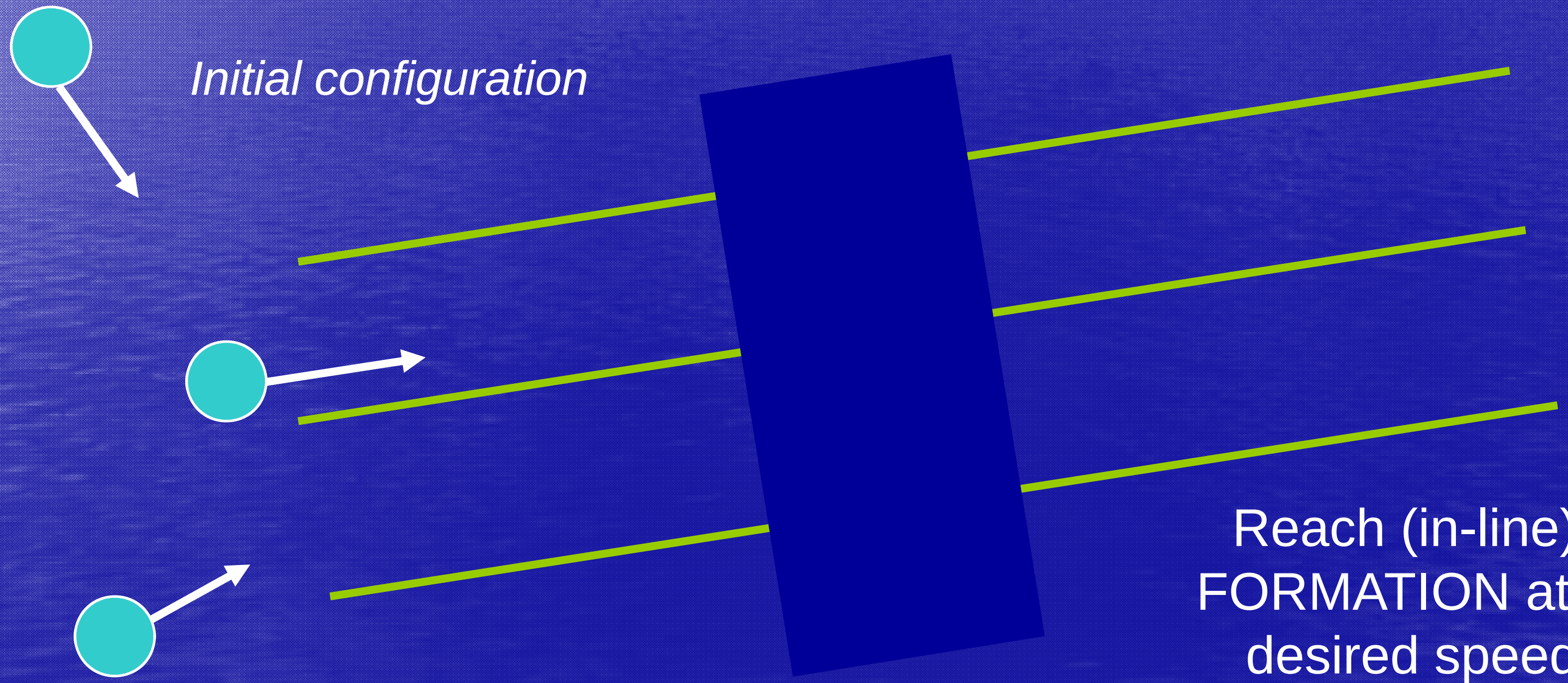
Solutio
too
comple

Too much
data
exchanged
between
the vehicles

“Combined Trajectory Tracking and Path Following: an Application to the Coordinated Control of Autonomous Marine Craft,” P. Encarnação and A. Pascoal, *40th IEEE Conference on Decision and Control*, Orlando, Florida, USA, Dec. 2001

Coordinated Path Following

(a fresh start)



PATHS (HIGHWAYS TO BE FOLLOWED)

Initial configuration

Reach (in-line)
FORMATION at a
desired speed

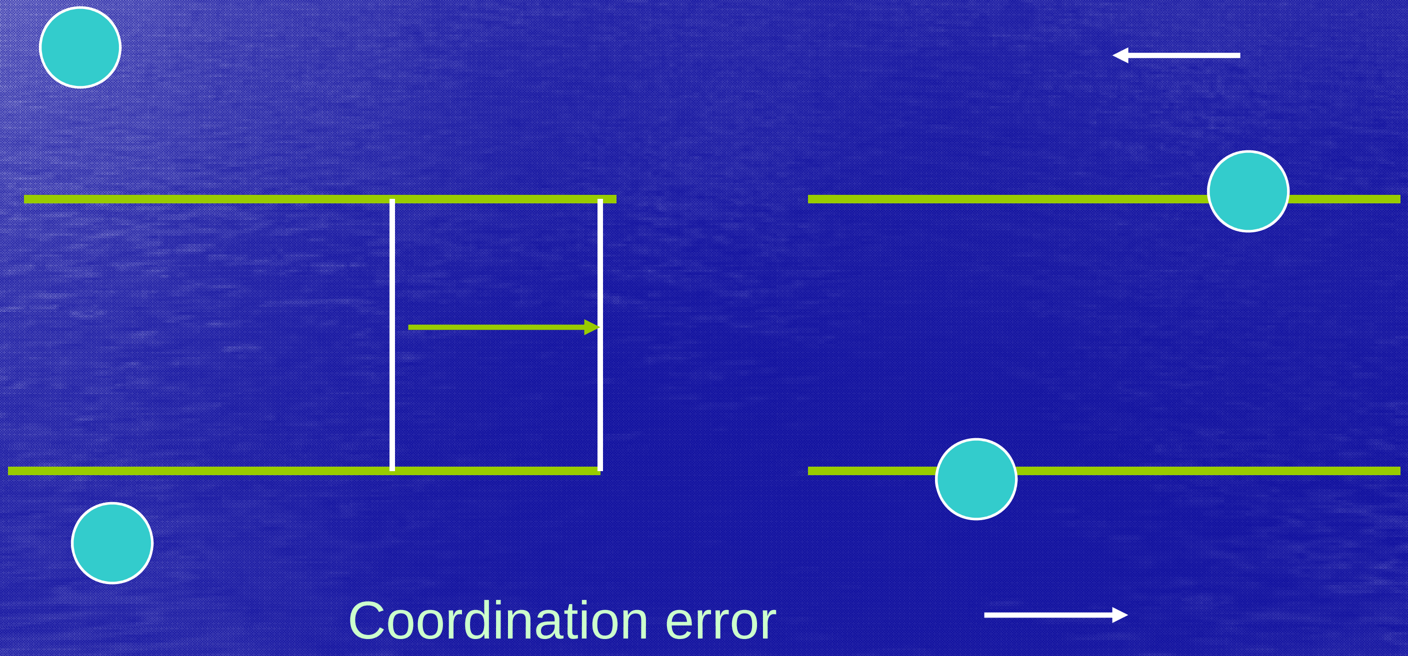
$\boxed{V_L}$ *!*

IN-LINE FORMATION

Divide to Conquer Approach

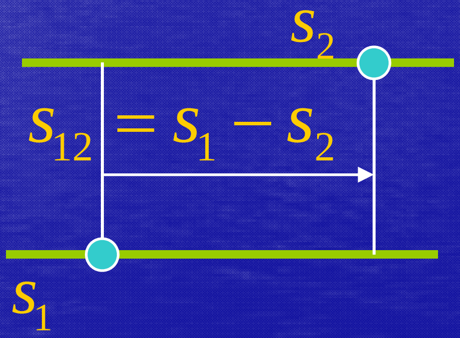
Each vehicle runs its own PATH FOLLOWING controller to steer itself to the path

Vehicles TALK and adjust their SPEEDS in order to COORDINATE themselves (reach formation)



Coordination state / error

Coordination error
(in-line formation): s_{12}



Path lengths s_1 and s_2

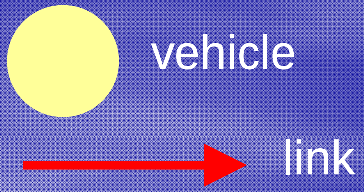
Coordinated Path Following (using the "inter-rabbit" distance)

L. Lapierre, D. Soetanto, and A. Pascoal (2003). Coordinated Motion Control of Marine Robots. *Proc. 6th IFAC Conference on Manoeuvering and Control of Marine Craft (MCMC2003)*, Girona, Spain.

R. Skjetne, I.-A. F. Ihle, and T. I. Fossen (2003) Formation Control by Synchronizing Multiple Maneuvering Systems. *Proc. 6th IFAC Conference on Manoeuvering and Control of Marine Craft (MCMC2003)*, Girona, Spain.

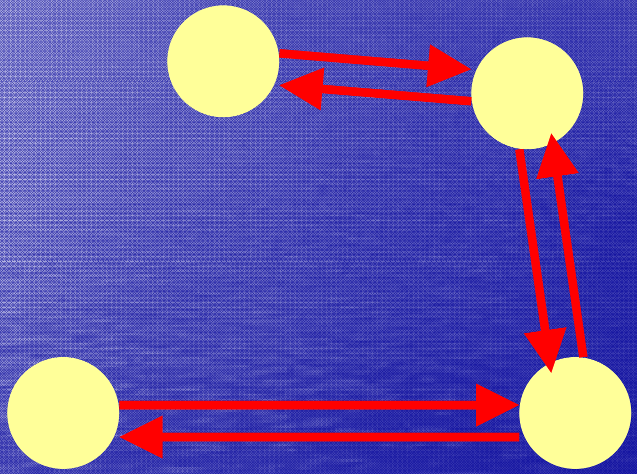
M. Egerstedt and X. Hu (2001) Formation Constrained Multi-Agent Control, IEEE Trans. on Robotics and auto., vol. 17, no. 6, Dec. 2001

They **do not address communication constraints** explicitly.

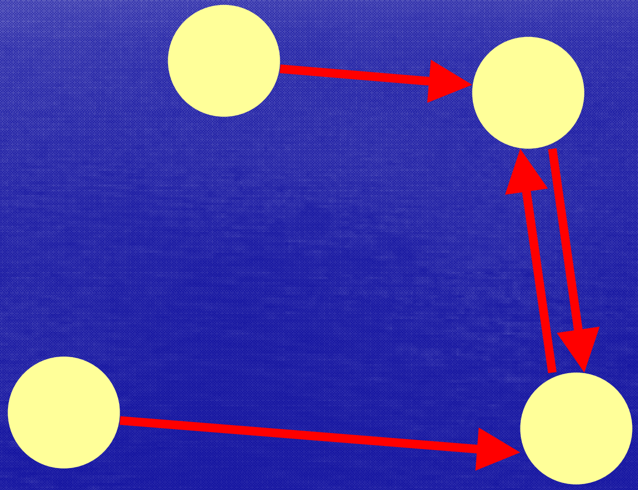


Communication Constraints

What is the communications topology? (**GRAPH**)



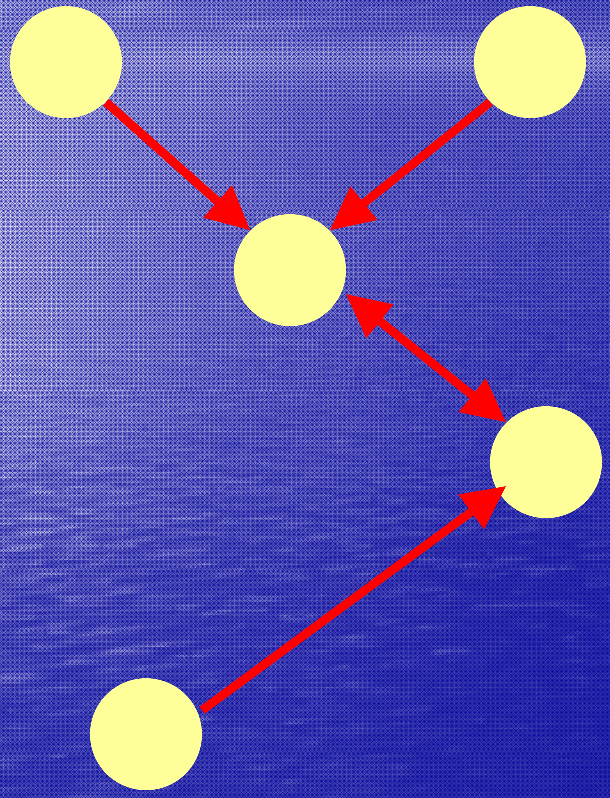
Bidirectional Links
→ *undirected graphs*



Non-bidirectional links
→ *directed graphs*

R. Murray [2002], B. Francis [2003], A. Jadbabaie [2003]

Communication Constraints

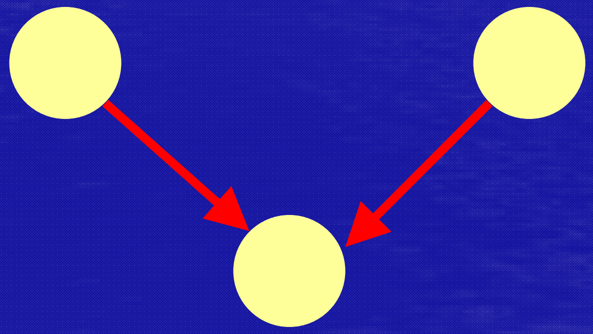


Communication Delays

Temporary Loss of Comms

Switching Comms Topology

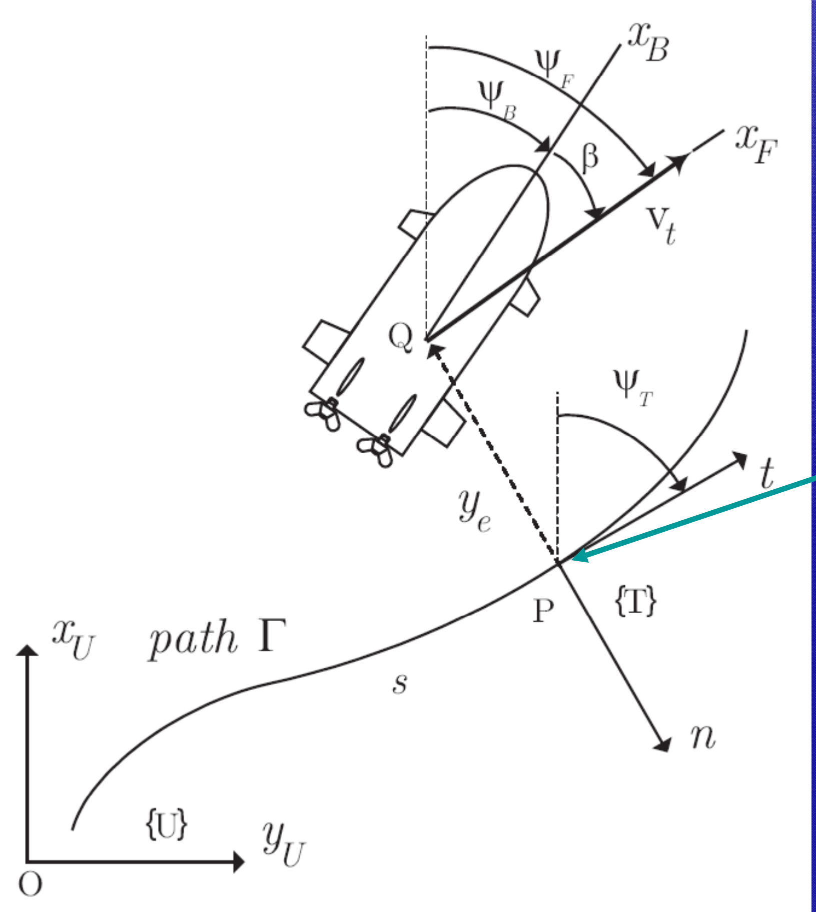
Asynchronous Comms



Links with Networked Control and Estimation Theory

SINGLE VEHICLE, PATH FOLLOWING

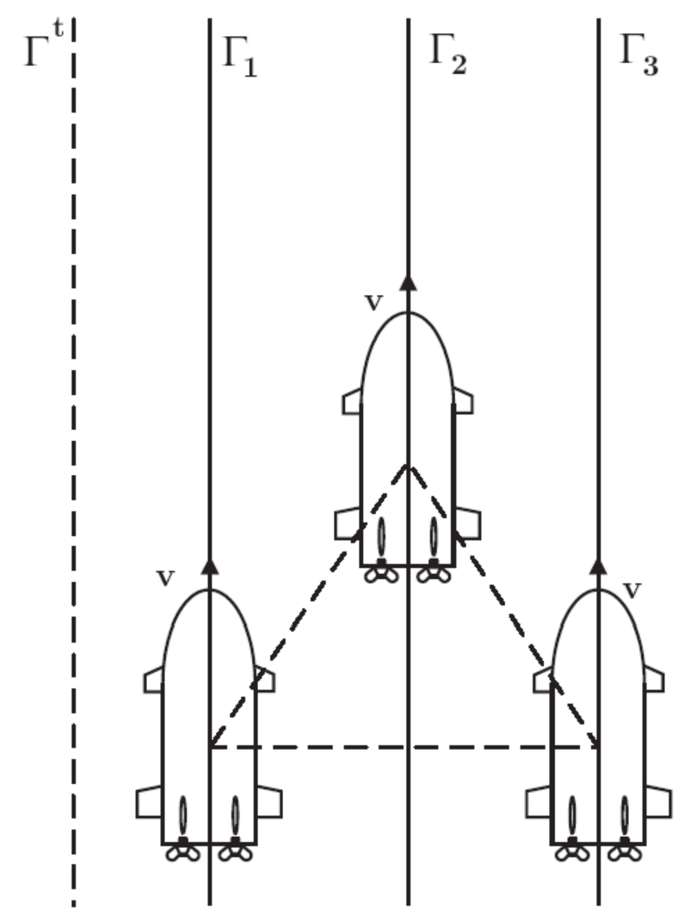
1. Drive the distance from Q to the rabbit to zero;
2. Align the flow frame with the Serret-Frenet
 (align total velocity V_t with the tangent to the path).



This will make
the vehicle follow the path

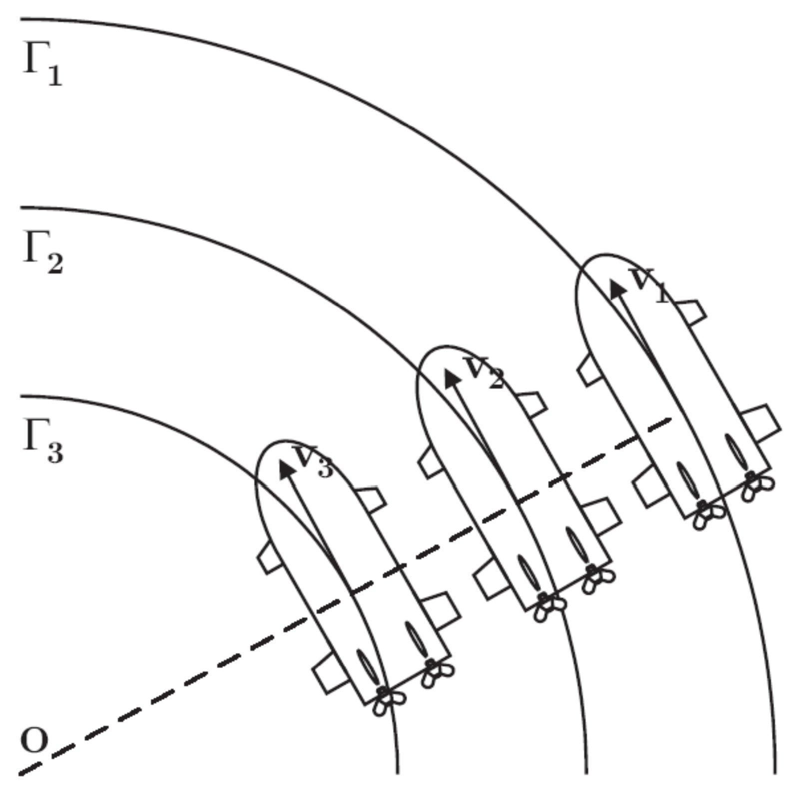
“guide” (rabbit) moving
along the path – “a mind
of its own” (control variable)

COORDINATED PATH FOLLOWING



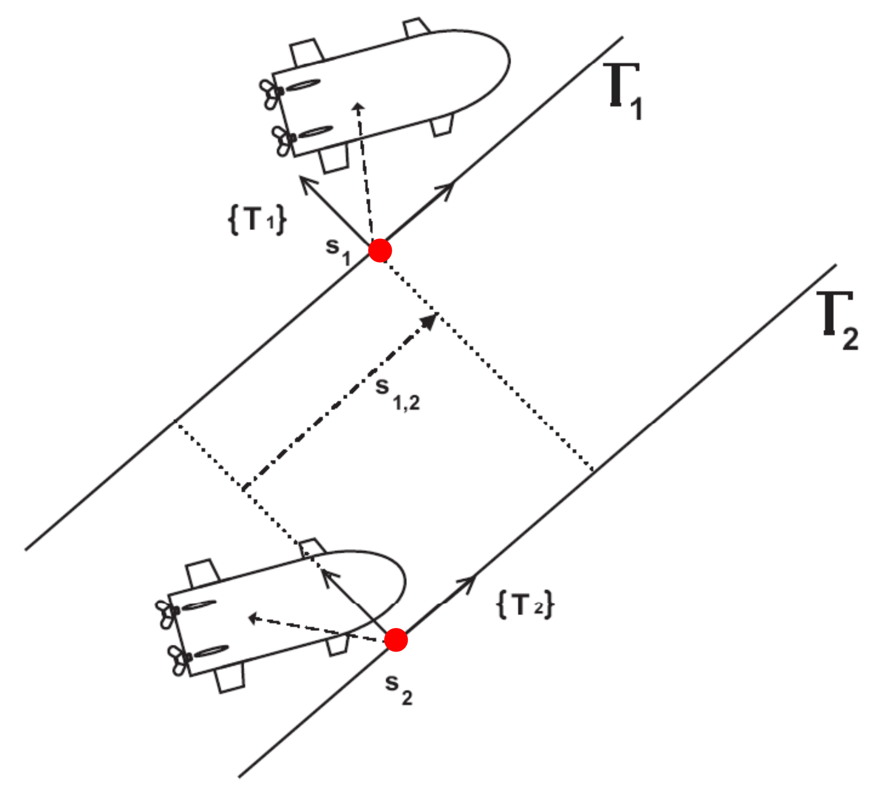
Triangle formation

More general formations and paths

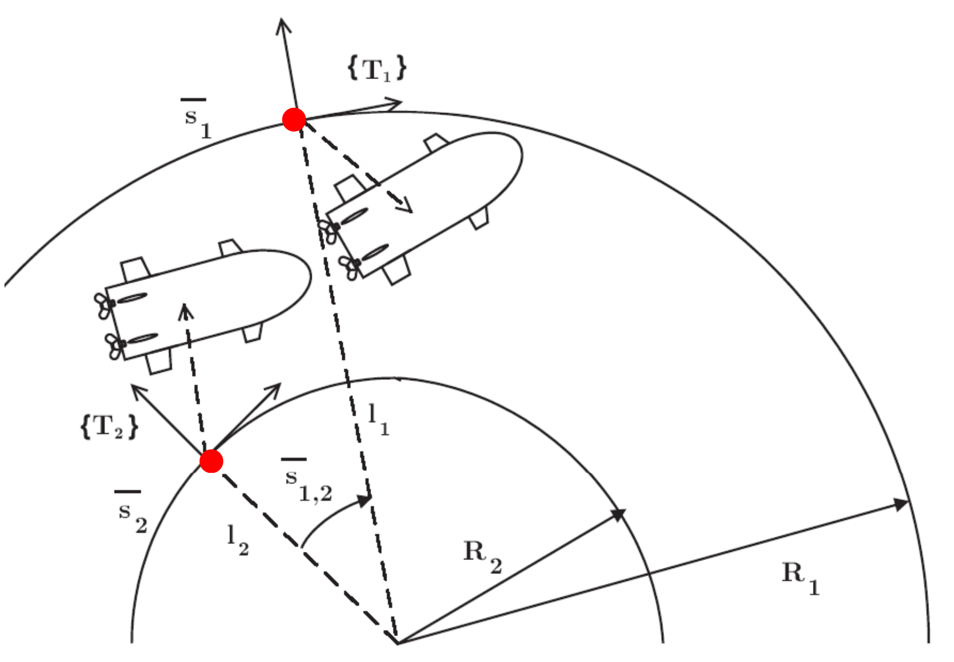


In-line formation

COORDINATED PATH FOLLOWING

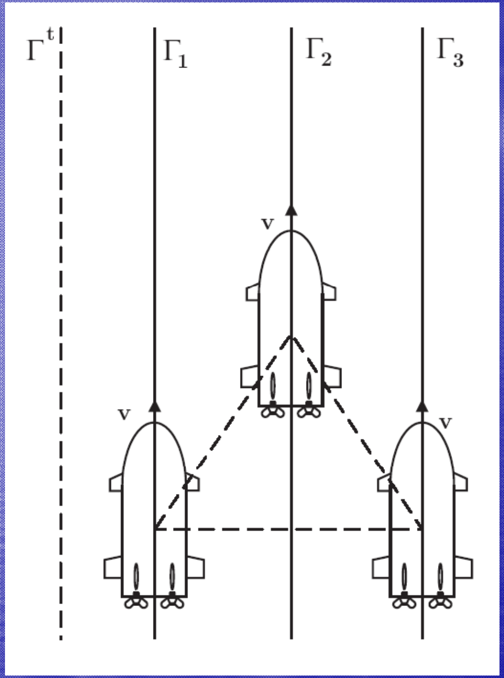


Coordination Error =
error between the "rabbits"



Generalizable to multiple vehicles and other formation patterns, and paths

COORDINATED PATH FOLLOWING



KEY INGREDIENTS:

PATH FOLLOWING for each vehicle

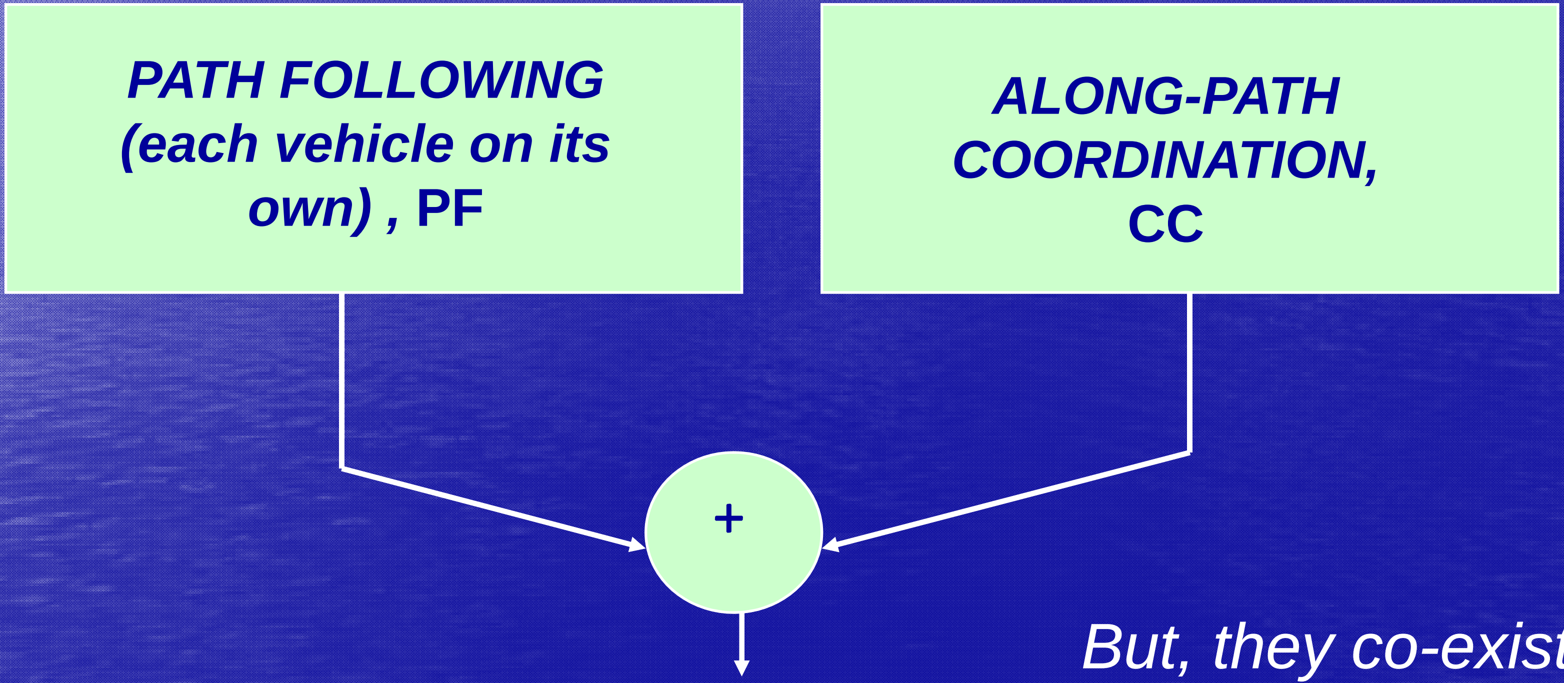
+

Inter-vehicle **COORDENATION**

(driving the coordination errors to zero:
speed adjustments based on
VERY LITTLE INFO EXCHANGED)

(**space-time decoupling** … maths work out!)

Divide to Conquer Approach



***PATH FOLLOWING (each vehicle on its own)* , PF**

***ALONG-PATH COORDINATION,* CC**

+

***COORDINATED PATH FOLLOWING* CPF**

But, they co-exist.
Analyze in detail!

Key results

Coordination achieved with

- *fixed communication networks*

  (ICAR’05, CDC’05, IJACSP)

- *brief connectivity losses, general comm. losses, and time delays*

  (SIAM-submitted, CDC’06, MCMC’06)

Fixed comm. networks

(ICAR'05, CDC'05, IJACSP)

Outline

- Path following: single vehicle
- Coordination error & path reparameterization
- Coordination dynamics
- Communication constraints & graphs
- Coordination control

Path following (single vehicle)

Vehicle: *wheeled robot* (underactuated vehicle w/no side-slip)

Control signal: angular speed

Asymptotic convergence to the path.

Condition:

$$\boxed{\int_0^\infty |v(t)|dt = \infty}$$

Exponential convergence if

$$\boxed{v \geq v_m > 0}$$

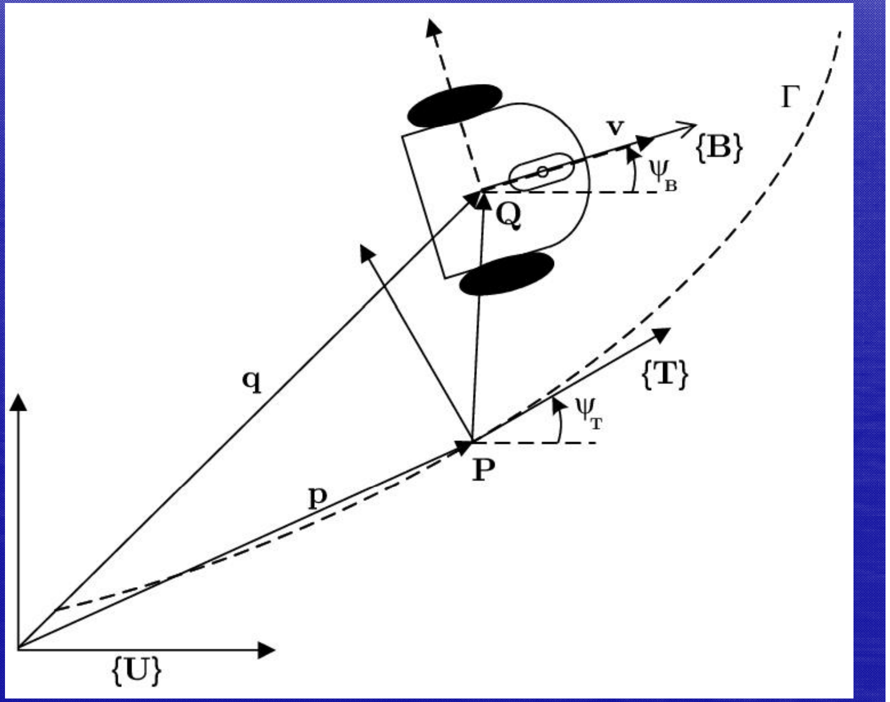
Path following (kinematics)

- Path following error vector and kinematics

$$\boxed{\begin{aligned}\dot{x}_e &= (y_e c_c(s) - 1)\dot{s} + v\cos\psi_e \\ \dot{y}e &= -x_e c_c(s)\dot{s} + v\sin\psi_e \\ \dot{\psi}_e &= r - c_c(s)\dot{s}\end{aligned}}$$

- ● *control signals*
- ● *exogenous signal*

$c_c(s)$ *path curvature at* P



Path following (problem)

$$\boxed{\text{dynamics:}\quad \dot{r} = \frac{1}{J}N; \quad \dot{v} = \frac{1}{m}F}$$

- **Problem:** Given a spatial path and a desired temporal profile v_d for the speed, derive feedback laws for N and $\dot{s}$ to drive $x_e, y_e, \psi_e, v - v_d$ to zero.

Path following, results

MAIN result: existence of control laws that solve the PF problem: error convergence is guaranteed

- if $v(t)$ is uniformly continuous and does not vanish asymptotically.

Path following (control strategy)

- Lyap. func. $$\boxed{\boldsymbol{V_p = \frac{1}{2}x_e{}^2 + \frac{1}{2}y_e{}^2 + \frac{1}{2}(\psi_e - \sigma(y_e))^2}}$$

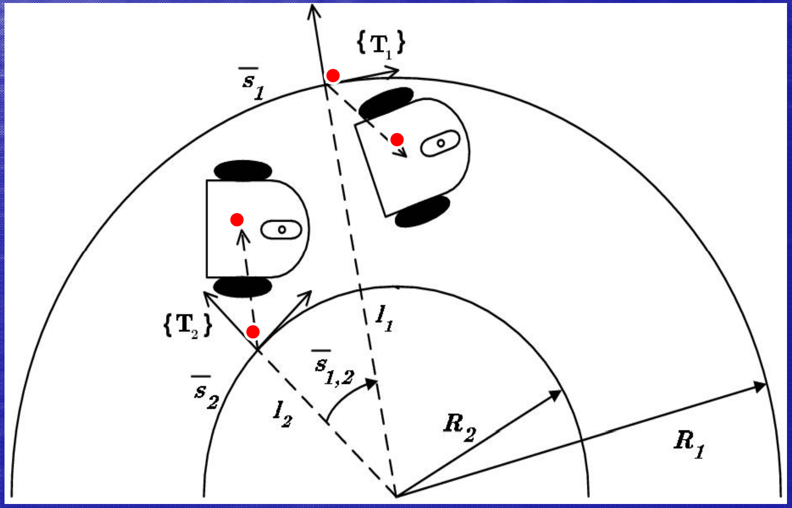
- approach angle $$\boxed{\sigma(y_e) = -\mathrm{sign}(v)\sin^{-1}\frac{k_2 y_e}{|y_e| + \varepsilon}}$$

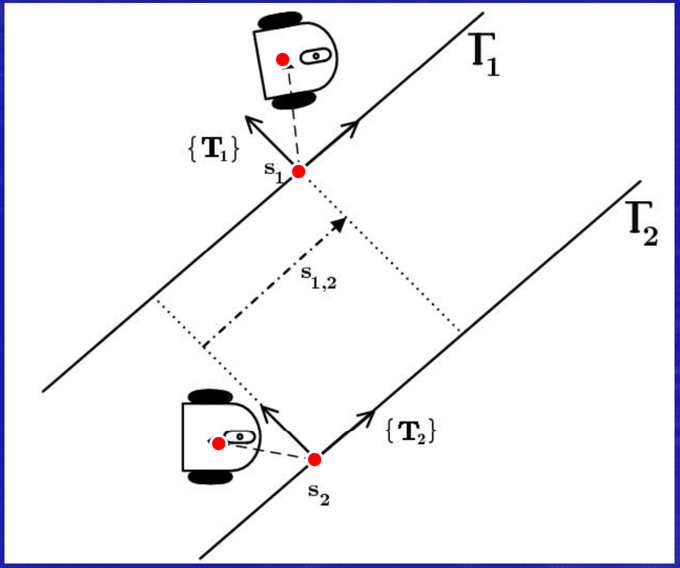
- time derivative
$$\dot{V}_p = -k_1 x_e{}^2 - k_2 |v(t)| \frac{y_e{}^2}{|y_e| + \varepsilon} + -k_3(\psi_e - \sigma)^2$$
  for some r and $\dot{s}$

- do back stepping to find N

Coordination state / coord. error

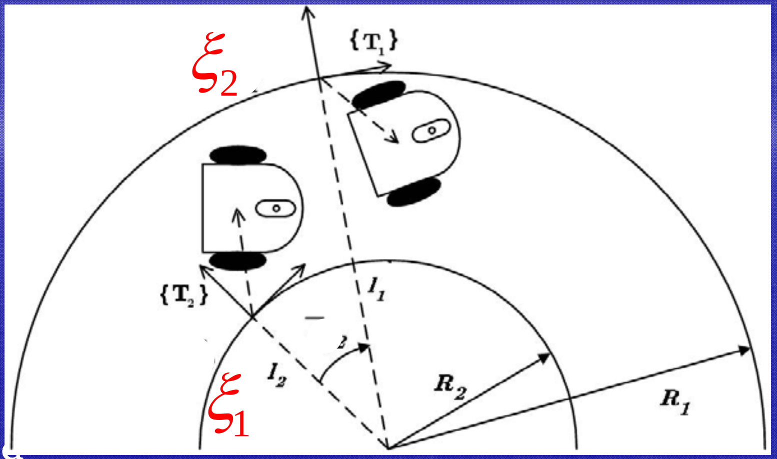
- Use the *RABBITS* to define the coordination error!
- Coordination is achieved if the coordination states (CSs) are equal,
- The CS is a geometrical variable: arc length (shifted paths), angle (circumferences), or even more general



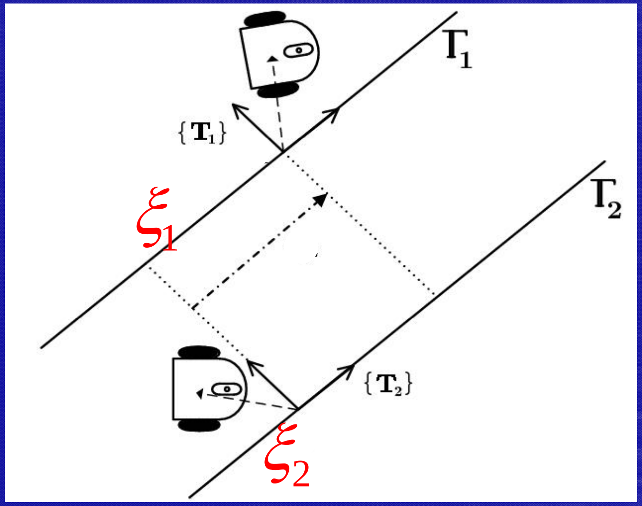


Coordination State / Path Reparametrization

- Paths parameterized by Vehicles *i* and *j* are coordinated if $\xi_i = \xi_j$
- Define the function (arc length) $s_i = s_i(\xi_i)$
- Define $\boxed{R_i = \frac{\partial s_i}{\partial \xi_i}}$



The choice of ξ_i must yield positive and bounded R_i



Shifted paths: $\boxed{s_i = \xi_i; \quad R_i(\xi_i) = 1}$

Circumferences:

$$\boxed{s_i = R_i \xi_i, \quad R_i(\xi_i) = R_i \ \text{(radii)}}$$

Coordination State / Path Reparametrization

45-degree example

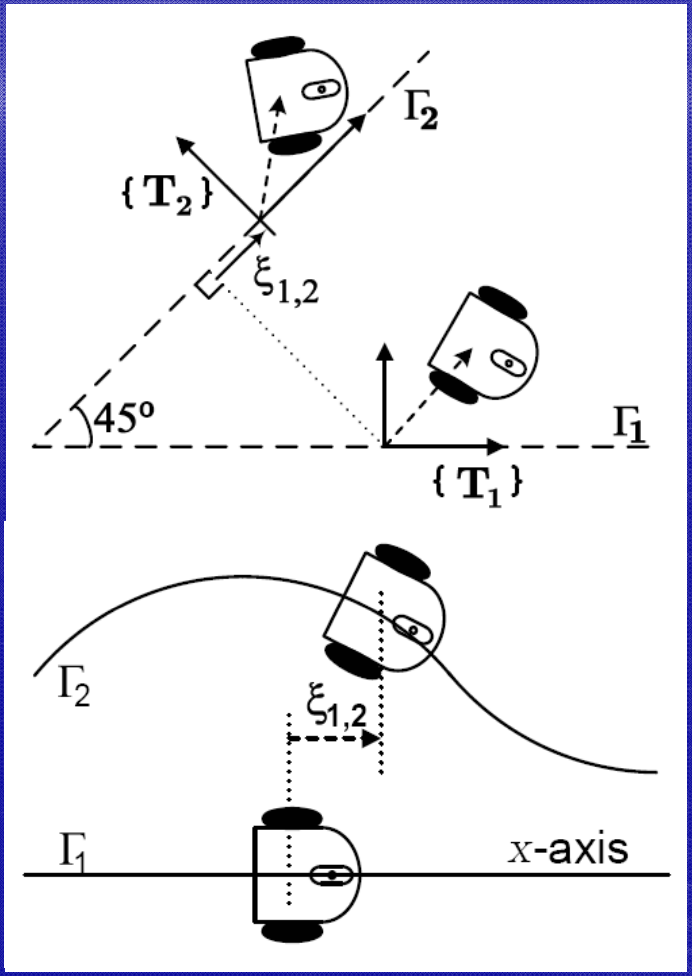
$$\xi_1 = s_1; \quad \xi_2 = \sqrt{2} s_2$$

$$R_1 = 1; \quad R_2 = \sqrt{2}$$

Sinusoidal example

$$\xi_1 = x_1 = s_1; \quad \xi_2 = x_2$$

$$R_1 = 1; R_2 = \frac{ds_2}{d\xi_2} = \sqrt{1 + \cos^2 \xi_2}$$



Coordination state dynamics-1

- The rabbit's dynamic for vehicle *i*

$$\boxed{\dot{s}_i = v_i + (\cos\psi_{e,i} - 1)v_i + k_1 x_{e,i}}$$

- Dynamics of coordination state *i*

$$\boxed{\dot{\xi}_i = \frac{1}{R_i(\xi_i)}\dot{s}_i \Rightarrow \quad \dot{\xi}_i = \frac{1}{R_i(\xi_i)}v_i + d_i}$$

IMPORTANT: d_i is guaranteed to vanish at the path following level

IF

v_i does not blow up and v_i does not tend to 0 (CAVEAT!)

The effect of the PF subdynamics appears as a "vanishing" disturbance in the Coo subdynamics.

Coordination state dynamics-2

- *Objectives:*

$$\boxed{\begin{array}{ll} \xi_i - \xi_j = 0 & \text{coordination} \\ \dot{\xi}_i = v_L & \text{formation speed} \end{array}}$$

- *Making* $d_i = 0$ *from* $\dot{\xi}_i = \dfrac{1}{R_i(\xi_i)} v_i + d_i$

desired speed of vehicle i equals $R_i(\xi_i) v_L$

- *define the speed tracking error*

$$\boxed{\begin{array}{l} \eta_i := v_i - R_i v_L \\ \dot{\eta}_i = f_i := \dfrac{1}{m} F_i - \dfrac{d}{dt} R_i v_L \end{array}}$$

Coordination subsystem

Complete Fleet of Vehicles

$$\dot{\eta} = f \quad \textit{CONTROL VARIABLE}$$

$$\dot{\xi} = C\eta + v_L 1 + d$$

Make d equal to 0.

Bring it into the picture at a later stage

- C is a state-driven varying matrix: $C_{ii} = \frac{1}{R_i(\xi_i)}$

  and $0 < c_1 \leq C(\xi) \leq c_2$

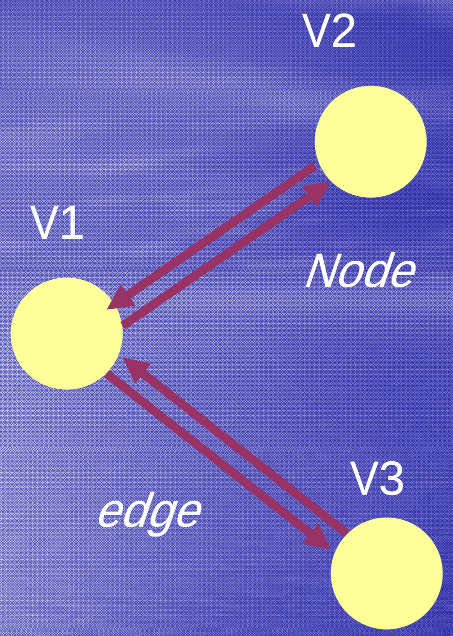
- Problem: Derive a control law for f so that

  $\eta_i, \xi_i - \xi_j$ converge asymptotically to zero.

Communication topology comes into play

use *Graph theory*

Communication Constraints



$$\text{Adjacency Matrix } A = \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

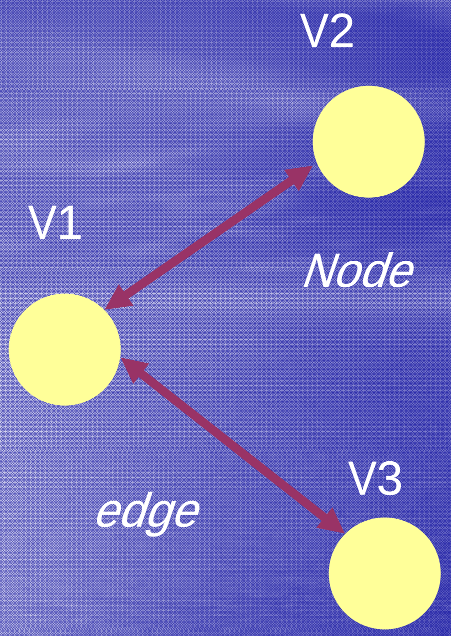
$$\text{Degree Matrix } D = \begin{bmatrix} 2 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

V1 receives info from *neighbours* V2 and V3

V2 receives info from *neighbour* V1

V3 receives info from *neighbour* V1

Communication Constraints



$$\longrightarrow$$

Laplacian

$$L = D - A = \begin{pmatrix} 2 & -1 & -1 \\ -1 & 1 & 0 \\ -1 & 0 & 1 \end{pmatrix}$$

$$L \begin{pmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \end{pmatrix} = \begin{pmatrix} (\xi_1 - \xi_2) + (\xi_1 - \xi_3) \\ \xi_2 - \xi_1 \\ \xi_3 - \xi_1 \end{pmatrix}$$

Neighbour set 1={ V2 , V3}

Neighbour set 2={ V1}

Neighbour set 3={ V1}

Properties:

- $L1 = 0$

-Graph is connected $\Rightarrow \operatorname{rank} L = n - 1 = 2$

$$L\xi = 0 \Rightarrow \xi_1 = \xi_2 = \xi_3$$

Communication constraints

- info available from a subset of the fleet: the neighboring vehicles, sets $\boxed{N_i}$
- bi-directional or directed communications.
- use graph Laplacian $\boxed{L}$ to model communication constraints declared by sets $\boxed{N_i}$

Coordination strategies

Complete Fleet of Vehicles (for $d = 0$)

$$\boxed{\begin{aligned}\dot{\eta} &= f \\ \dot{\xi} &= C\eta + v_L 1\end{aligned}}$$

- Comm. graph is undirected and connected
- (MAIN results) either of the following control laws solve the CC problem

$$\boxed{\begin{aligned} f &= -A\eta - BCL\xi \\ f &= -(LC + C + A)\eta - AL\xi \\ f &= -(A^{-1}L + A)C\eta - B\mathrm{sat}(\eta + A^{-1}L\xi) \end{aligned}}$$

- L : underlying comm. graph Laplacian
- A, B : positive diagonal matrices
- $\mathrm{sat}(.)$: saturation function

Coordination strategies

vehicle *i*, decentralized form

$$\boxed{\begin{aligned} f &= -A\eta - BCL\xi \\ f_i &= a_i\eta_i - \frac{b_i}{R_i}\sum_{j\in N_i} \xi_i - \xi_j \end{aligned}}$$

Challenges:
DONE!

1) when $C(\xi)$ is varying
2) prove $v_i(t)$ satisfies required conditions when putting together PF and CC

Switching comm. / failures / time delays
are very important issues
→ *next part of the talk*

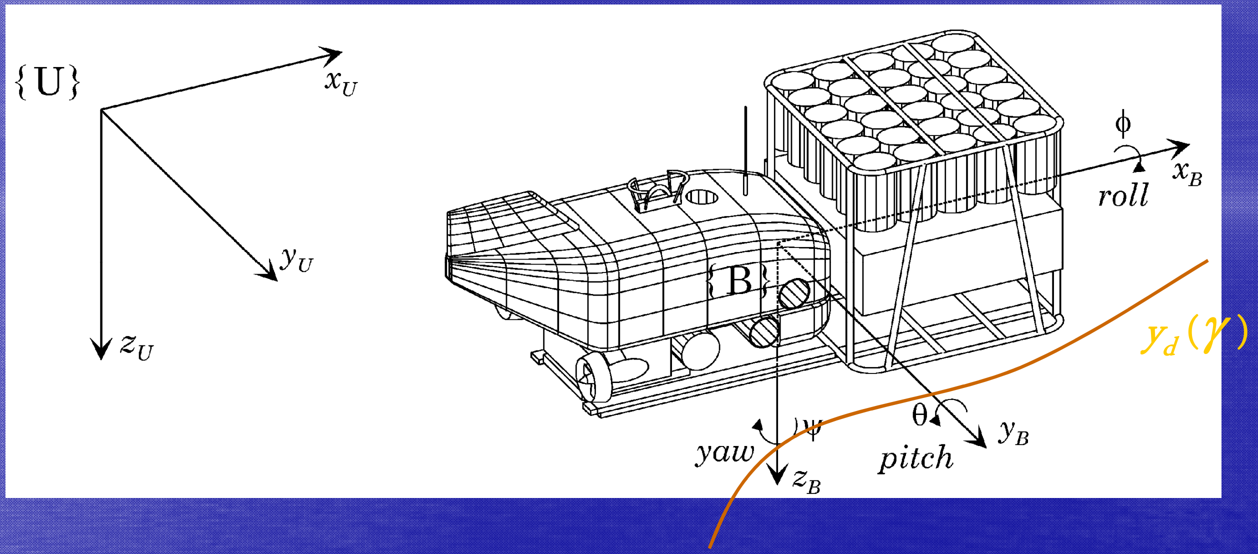
General Path Following algorithms Switching communications

Outline

- *General under-actuated vehicle, PF*
- *Coordination under*
  - *Brief connectivity losses*
  - *General communications losses*

  (Time delays)

Path following



- ***Path-following problem***
  - Given a geometric path $\left\{ y_d(\gamma) \in R^3 : \gamma \in R \right\}$ and a speed assignment $v_r(t)$, we want
    - the position of the vehicle to converge to and remain inside an arbitrarily thin tube centered around the desired path
    - satisfy (asymptotically) the desired speed assignment, i.e.,

$$\dot{\gamma} \rightarrow v_r \text{ as } t \rightarrow \infty$$

Path following

(a very general set-up)

Vehicle dynamics

$$\boxed{\begin{cases} \dot{x}_i = f_i(x_i, u_i) \\ y_i = h_i(x_i) \end{cases}}$$

PFollowing error

$$e_i(t) = y_i(t) - y_{d,i}(\gamma_i(t))$$

Speed tracking error

$$\eta_i(t) = \dot{\gamma}_i(t) - v_{r,i}(t)$$

Coordination, problem

Coo. Dyn. $\dot{\gamma}_i = v_{r,i} + \eta_i \quad i = 1, \ldots, n$

η_i a signal from PF closed-loop dyn.

Coordination problem:

- Derive a control law for $v_{r,i}$
- such that asympt. $\left|\gamma_i - \gamma_j\right| \to 0, \left|\dot{\gamma}_i - v_L\right| \to 0$
  - $v_L(t)$: a given formation speed profile

Comm. needed to *exchange information*
Comm. subjected to <u>change</u> and time <u>delays</u>

Coordination, control law

Proposed control

$$v_{r,i}(t) = v_L(t) - k_i \sum_{j \in N_{i,p(t)}} \gamma_i(t) - \gamma_j(t)$$

$p(t)$: a vector indicating which edge is active at time t

$N_{i,p(t)}$: Neighbors of vehicle i at time t

info. arrives with time delay

Coordination, closed-loop

Closed-loop dyn.
in vector form
no delays

$$\dot{\gamma} = -KL_{p(t)}\gamma + v_L 1 + \eta$$

Closed-loop dyn.
in vector form
with delays

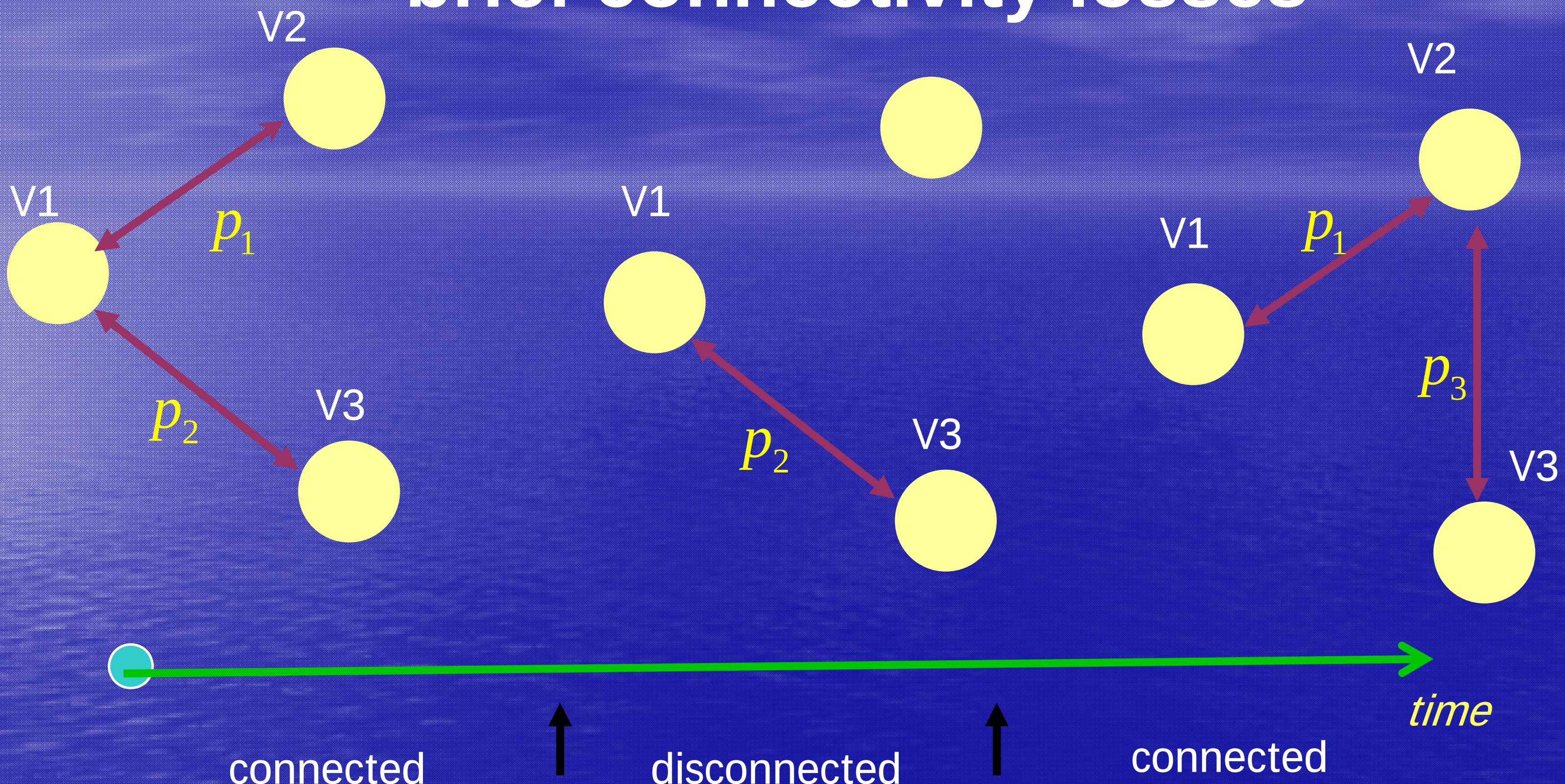
$$\dot{\gamma} = -KD_{p(t)}\gamma(t) + KA_{p(t)}\gamma(t-\tau) + v_L 1 + \eta$$

Two types of

switching comm.

considered

Switching Communication brief connectivity losses



$p_1 = 1, p_2 = 1, p_3 = 0$

$p_1 = 1, p_2 = 0, p_3 = 1$

$p_1 = 0, p_2 = 1, p_3 = 0$

L is a function of *p, denoted* L_p

Brief Connectivity Losses

- Inspired by the concept of “brief instabilities” - Hespanha et. Al. IEEETransactions AC 04
- **BCL:** the communication graph is connected and disconnected alternatively

Brief connectivity losses

Charac. function of switching topology : $\chi(p) = \begin{cases} 0 & \text{graph is connectd} \\ 1 & \text{graph is disconnectd} \end{cases}$

Connectivity loss time over $[t_1, t_2]$: $T_p(t_1, t_2) = \int_{t_1}^{t_2} \chi(p(t))dt$

The comm. Network has BCL if $T_p \leq \alpha(t_2 - t_1) + (1 - \alpha)T_0$

Asympt. connectivity loss rate: $0 \leq \alpha \leq 1$

Connectivity loss upper bound: $T_0 > 0$

Example: periodically
- 10 sec connected
- 40 sec disconnected

$\rightarrow \begin{cases} \alpha = 20\% \\ T_0 = 40 \end{cases}$

Brief connectivity losses

Connectivity loss time over $[t_1, t_2]$:

$$T_p(t_1,t_2) = \int_{t_1}^{t_2} \chi(p(t))dt$$

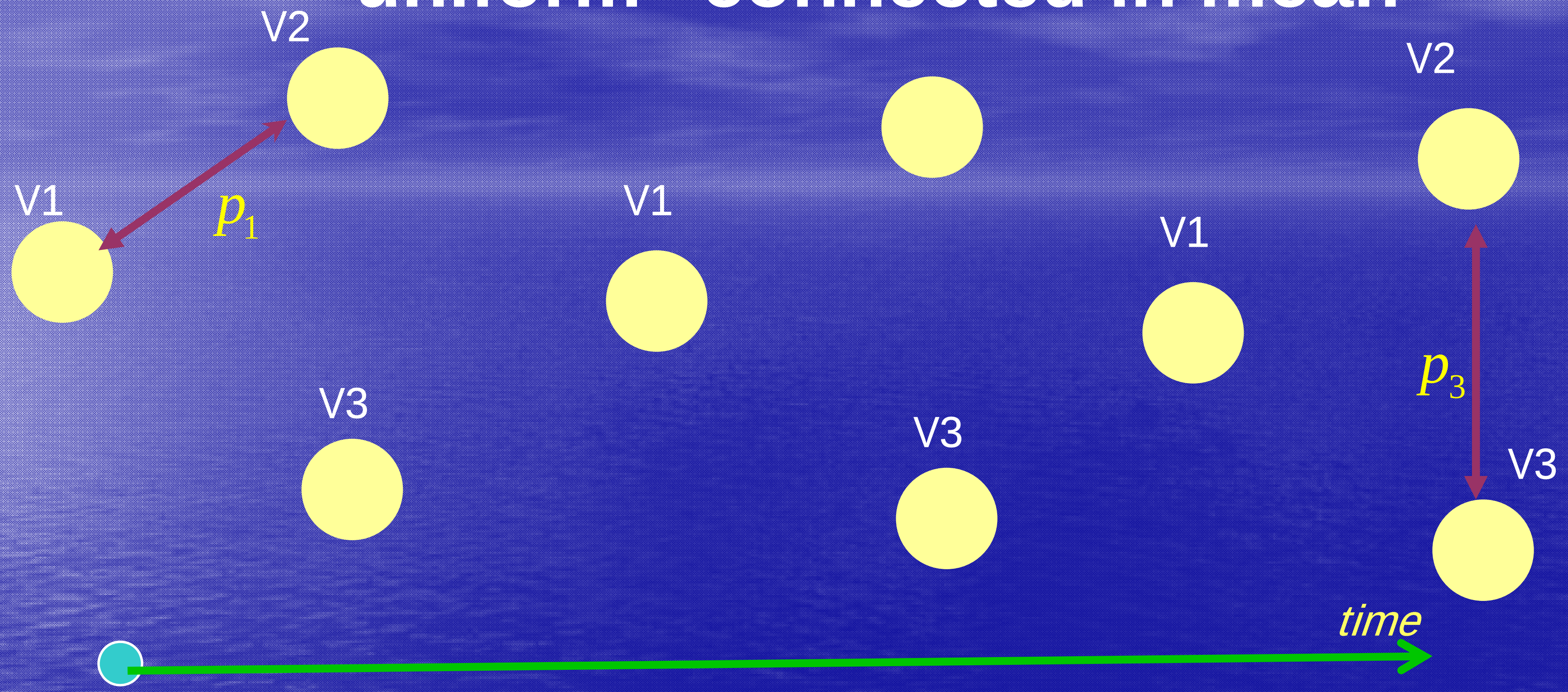
$$T_p \le \alpha(t_2 - t_1) + (1-\alpha)T_0$$

$$\boxed{\frac{T_p}{t_2 - t_1} \le \alpha + \frac{(1-\alpha)T_0}{t_2 - t_1} \Rightarrow \lim_{t_2 - t_1 \to \infty} \frac{T_p}{t_2 - t_1} \le \alpha}$$

If the graph is disconnected over $[t_1, t_2]$

$$\boxed{\begin{array}{l} T_p = t_2 - t_1 \\ T_p \le \alpha T_p + (1-\alpha)T_0 \Rightarrow T_p \le T_0 \end{array}}$$

Switching Communication
“uniform” connected in mean



$p_1 = 1, p_2 = 0, p_3 = 0$ ↑ $p_1 = 0, p_2 = 0, p_3 = 0$ ↑ $p_1 = 1, p_2 = 0, p_3 = 1$

L_{p_1} L_{p_2} L_{p_3}

the union graph over
time interval *T*
is connected

$$\boxed{L_{[t,t+T]} = L_{p_1} + L_{p_2} + L_{p_3}}$$

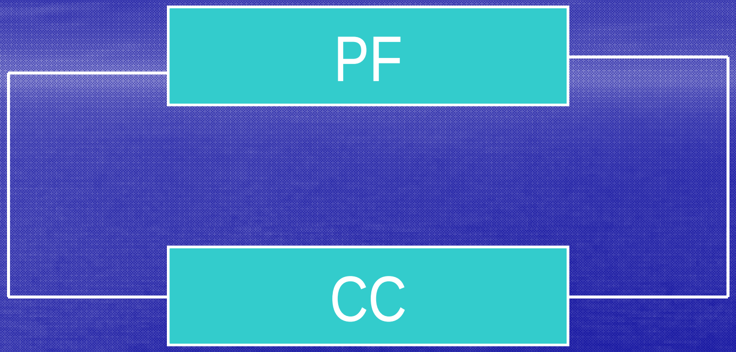
$$\boxed{\Rightarrow \begin{cases} \text{rank } L_{[t,t+T]} = n - 1 = 2 \\ L_{[t,t+T]} 1 = 0 \end{cases}}$$

Uniform Connected in Mean

- Inspired by work of
  - Moreau (CDC'04)
  - Lin, Francis, Maggiore (SIAM recent)
- **UCM:** there is a $T>0$, such that the union communication graph is connected over any time interval of length T

We assume a switching *dwell time* $\tau_D > 0$
(time clearance between two consecutive switches)

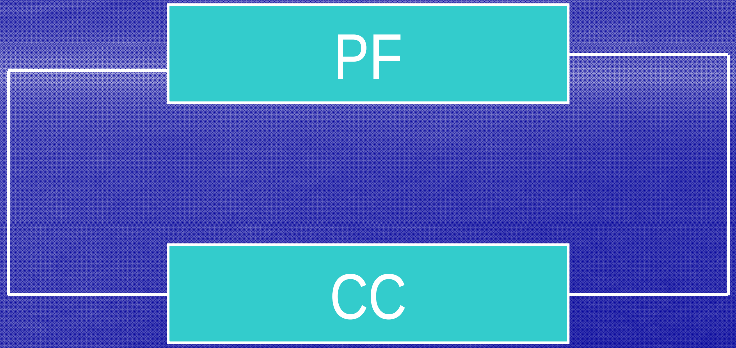
PF and CC interconection



Proof of convergence.

Key Ingredient: a new small gain theorem
for systems with brief instabilities

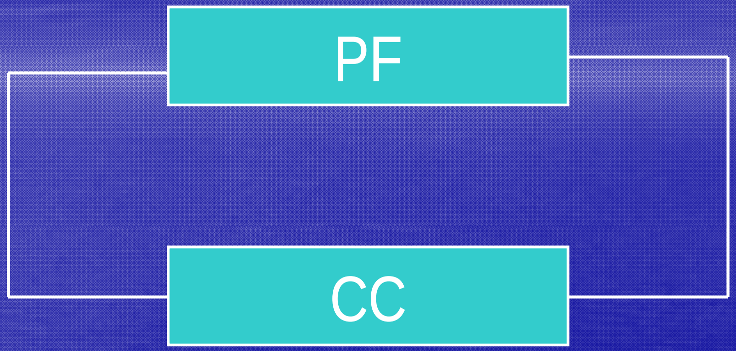
PF and CC interconection



Main Result A (Brief Connectivity Losses)

For any choice of connectivity parameters T and α, there exist PT and CC gains that yield convergence of the complete system error trajectories to an arbitrarily small neighborhood of the origin.

PF and CC interconection



Main Result B (Connected in Mean)

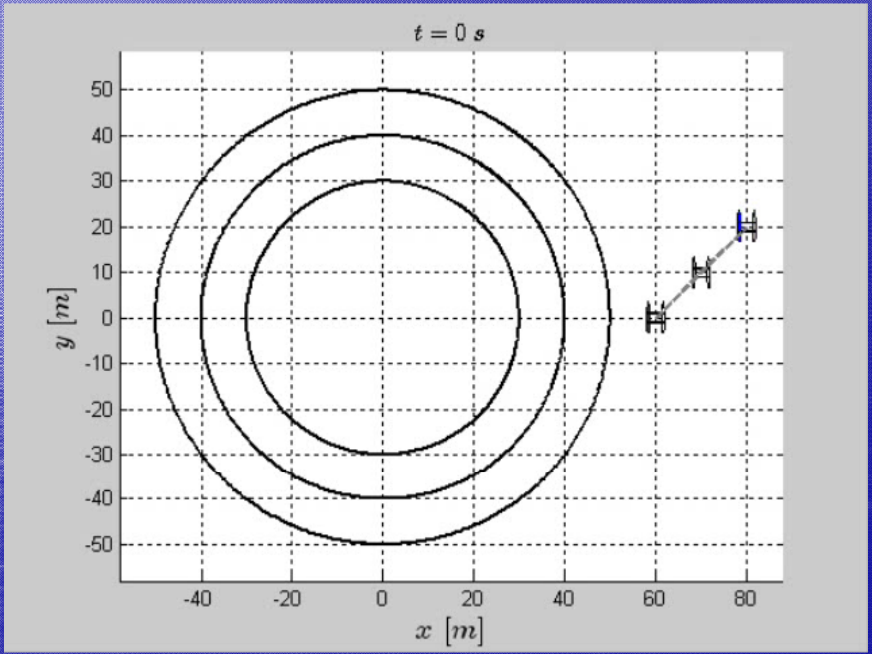
For any choice of average connectedness time T,
there exist PT and CC gains that yield convergence of the complete system error trajectories to an arbitrarily small neighborhood of the origin.

Summary

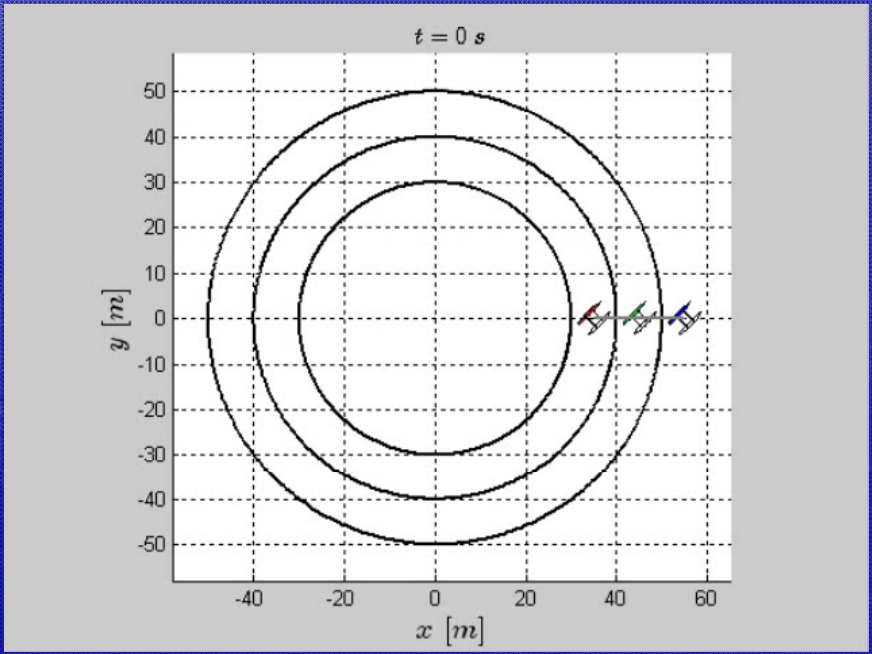
- Path following control for a general underactuated vehicle
- Coordination strategies under switching communications
  - Brief connectivity losses
  - Uniform connected in mean
- PF-CC interconnection

Simulations (ASCraft, fully actuated)

[João Almeida, MSc, IST]

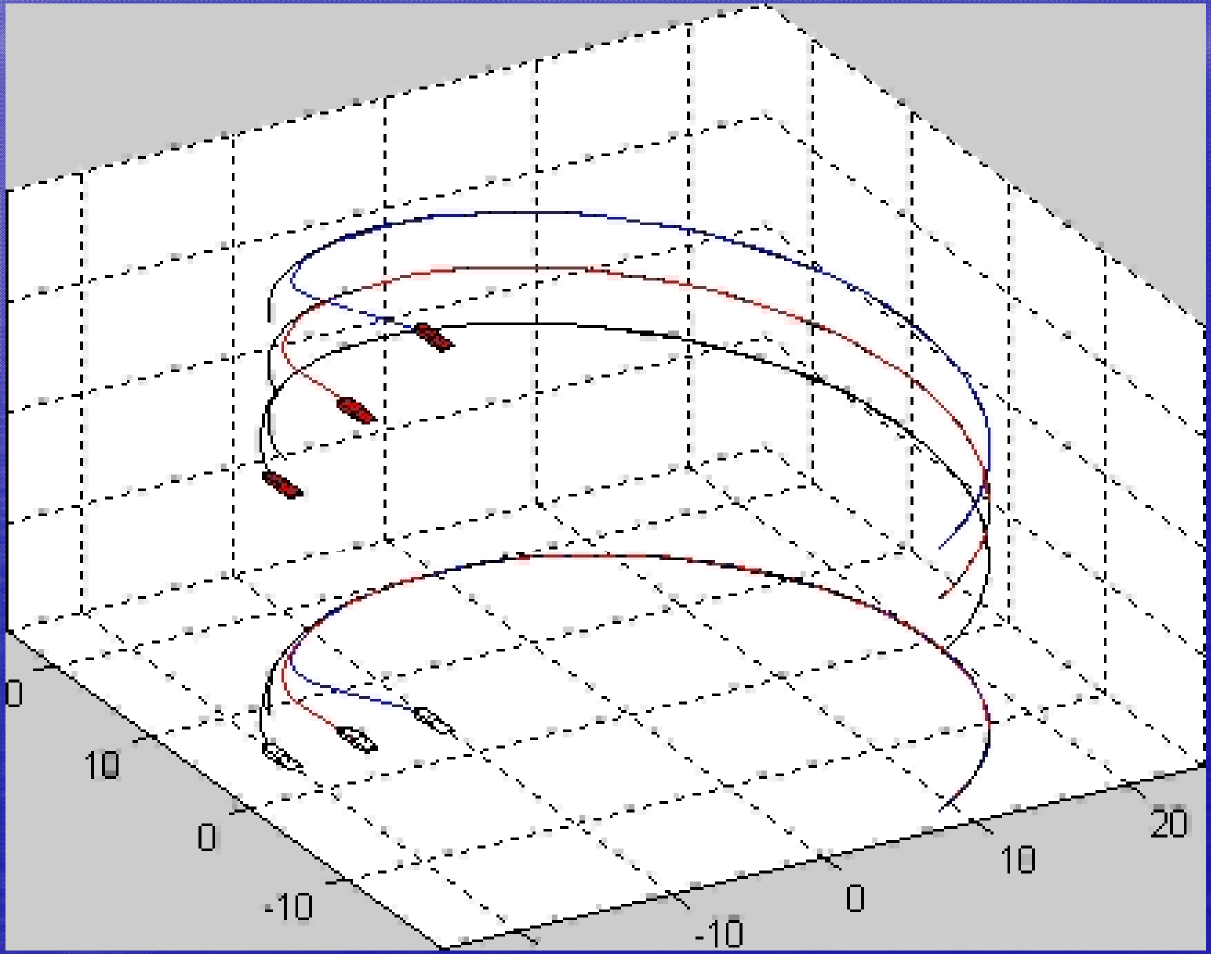


In-line formation



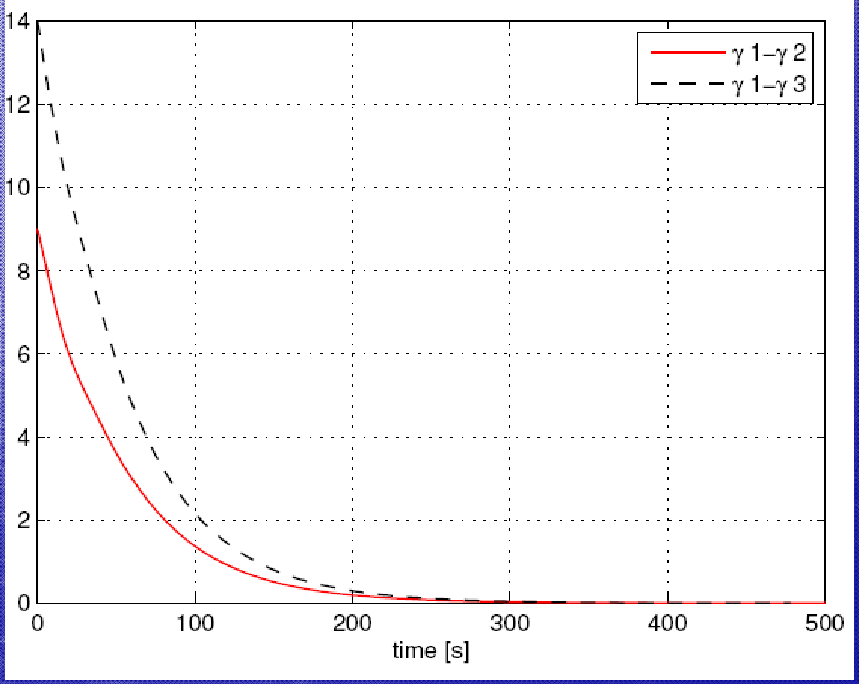
Triangle formation

Simulations

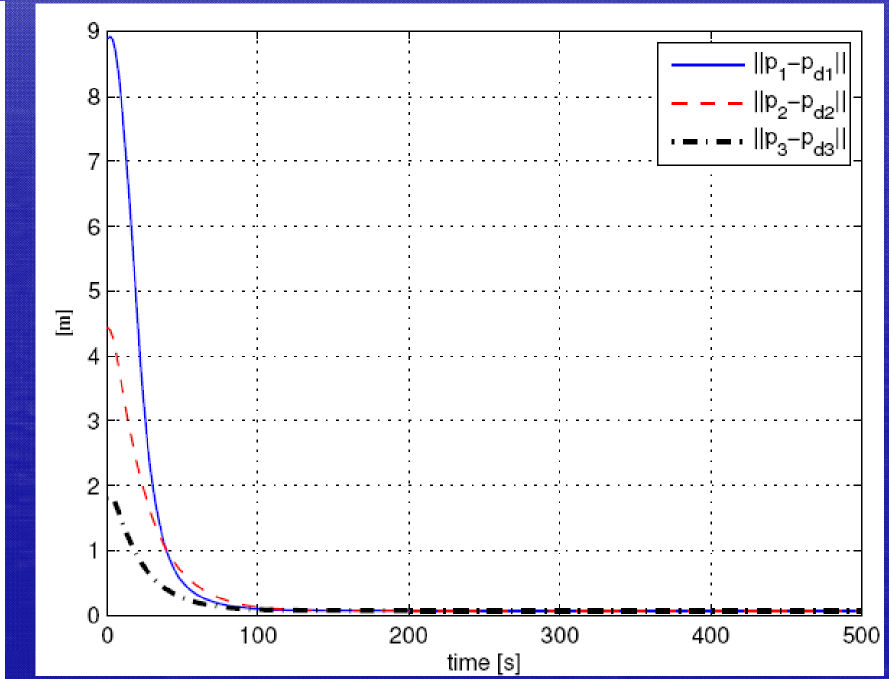


Simulations, no failures

coordination errors



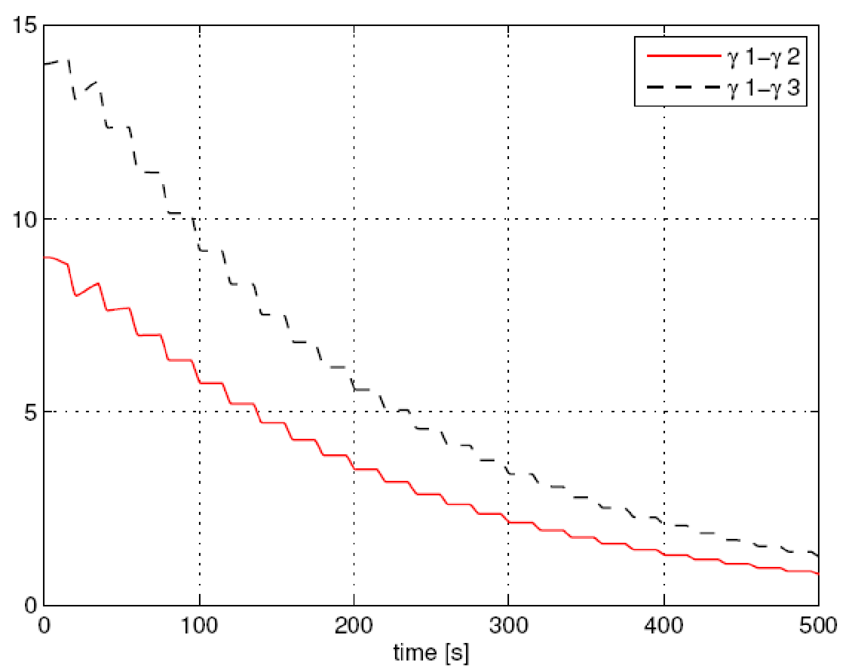
path following errors

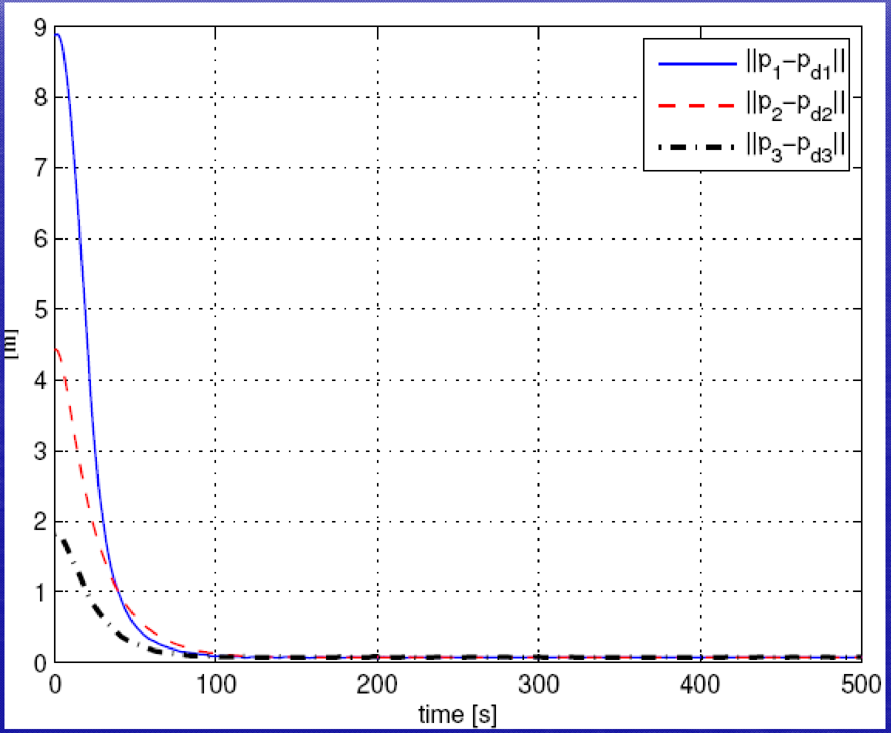


Simulations, 75% failures

coordination errors

path following errors





With 75% of communications failures occurring periodically with T=20s

Contributions, Coordinated control

- Fixed networks
  - Proper set-up for coordinated path following, general coordination patterns and paths.
  - Solutions for bidirectional and non-bidirectional networks.
  - Convergence guaranteed when putting together PF and CC systems (dynamics of the vehicle taken directly into account!)

Contributions, Coordination control

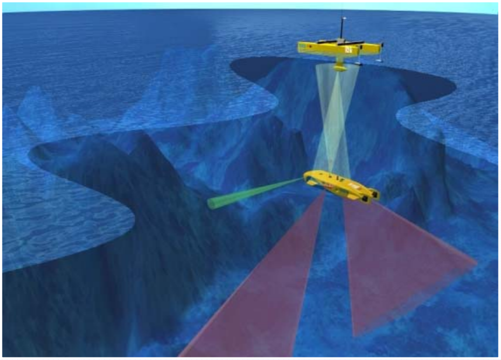
- Switching networks
  - Coordination guaranteed under switching communications
    - Brief connectivity losses
    - Uniform connectedness in mean
  - Switching communications with delays
  - Small gain theorem for systems with brief failures
    - convergence guaranteed when putting together PF and CC systems

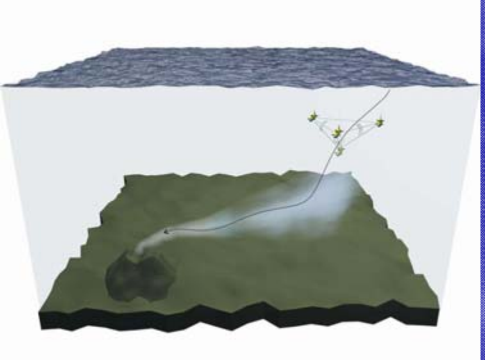
Communications

- . There is an underlying communication topology (fixed or time-varying)

- Communications DO NOT occur in a continuous manner – asynchronous, with delays

- There is a COST associated with communicating: comms should be parsimonious: *periodic (Antsaklis), asynchronous (Tsitsiklis, Athans, Bertsekas), Logic-Based (Xu and Hespanha).*





Theoretical Issues / Physical constraints

Energy constraints **– small vehicles, limited energy on-board.**

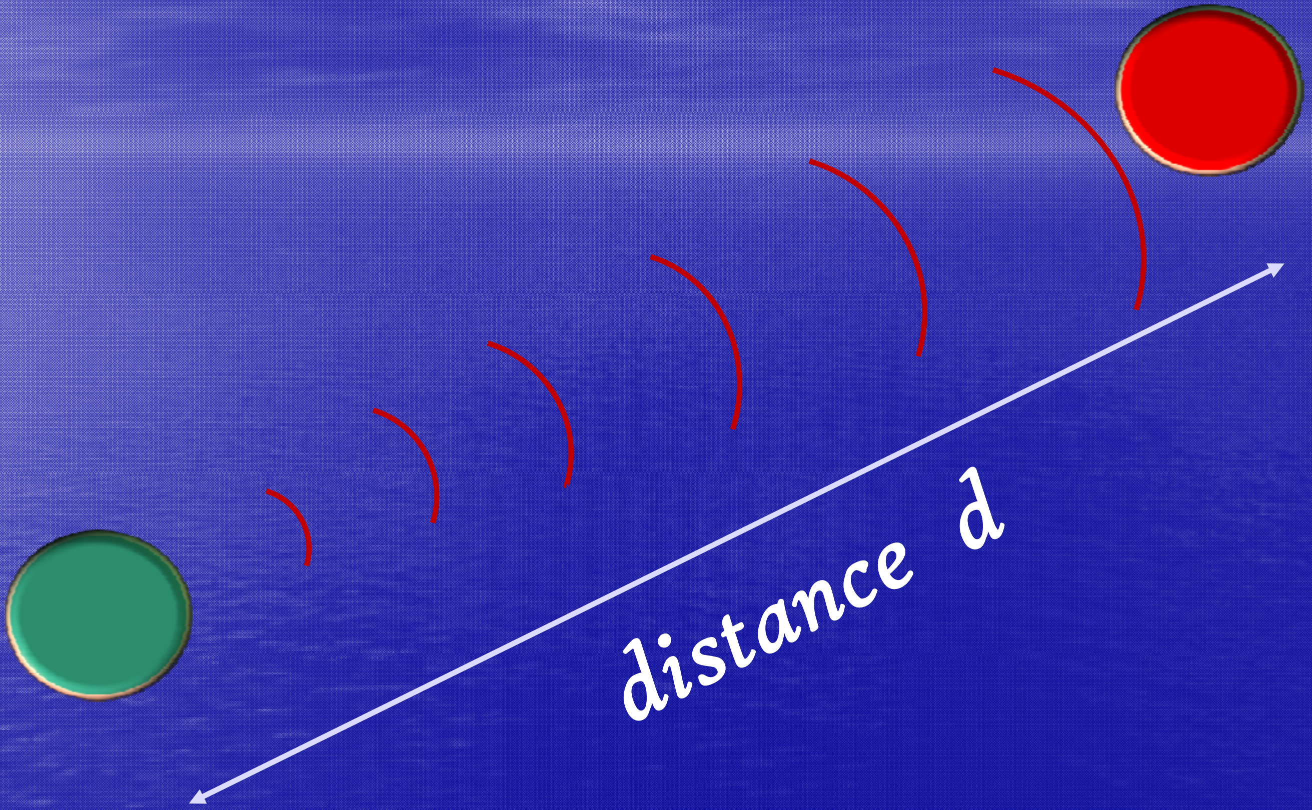
Low data rates **– 100´s bit/sec (slant range) in shallow waters**

Distance-dependent time delays

<u>What model best captures the communication losses?</u>

- Known delays - R. Ghabcheloo, A. Aguiar, A. Pascoal, C. Silvestre, "Synchronization in multi-agent systems with switching topologies and non-homogeneous communication delays ", CDC 2007.

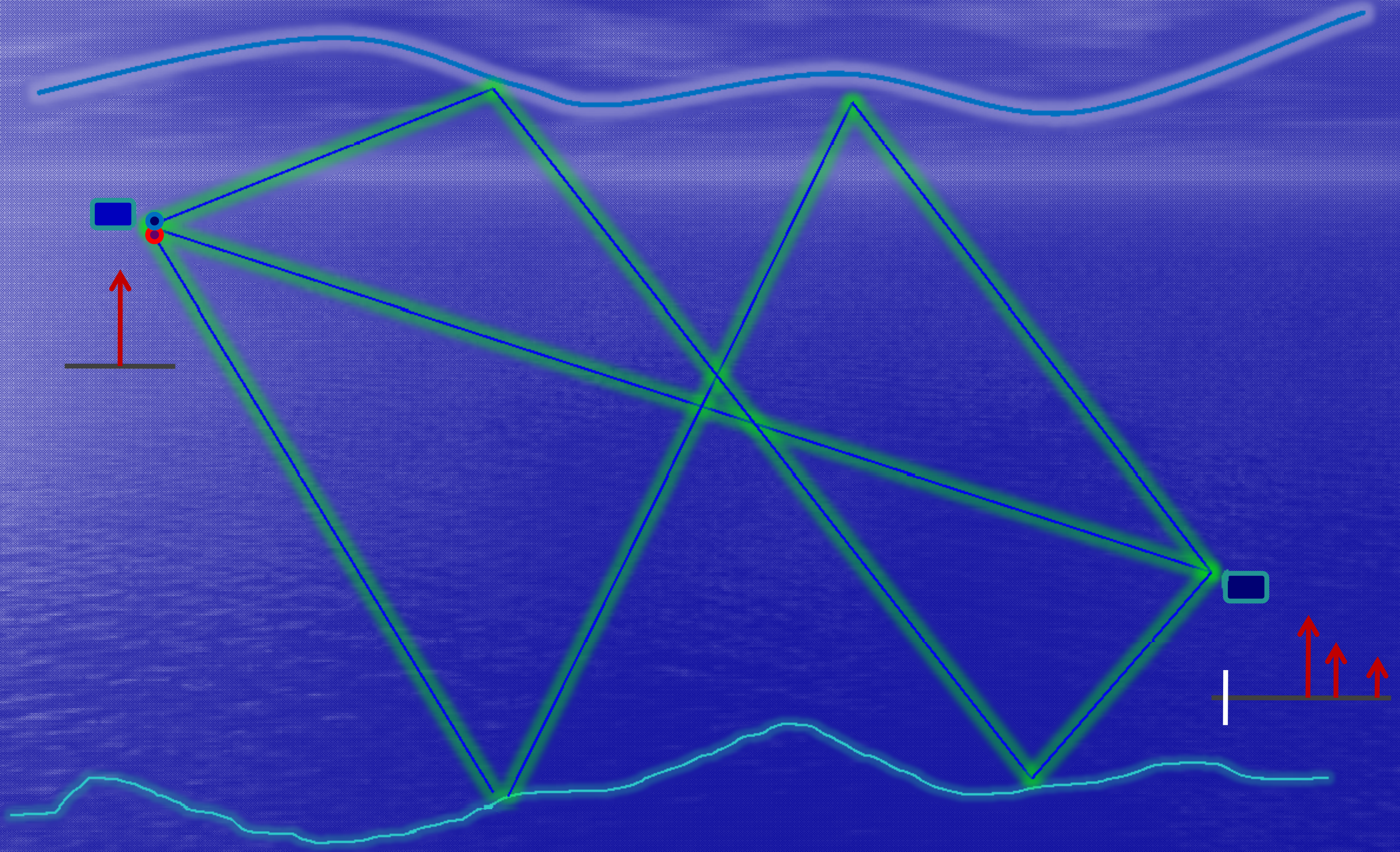
Communication delays



delay $\tau = d / c$; c = speed of sound

NetMar$_{SyS}$

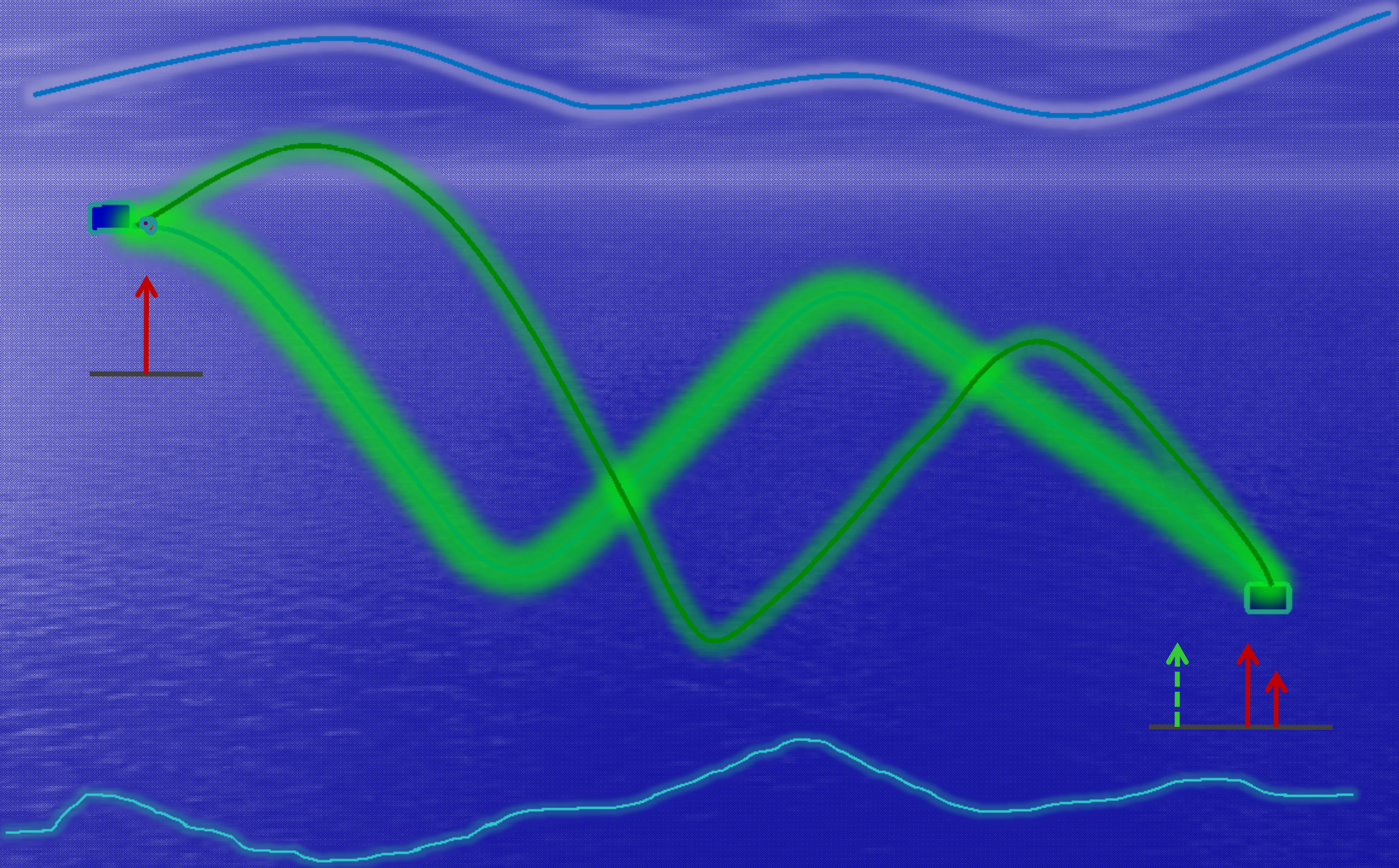
Acoustic Channel



Channel impulse response - multipaths

NetMar SyS

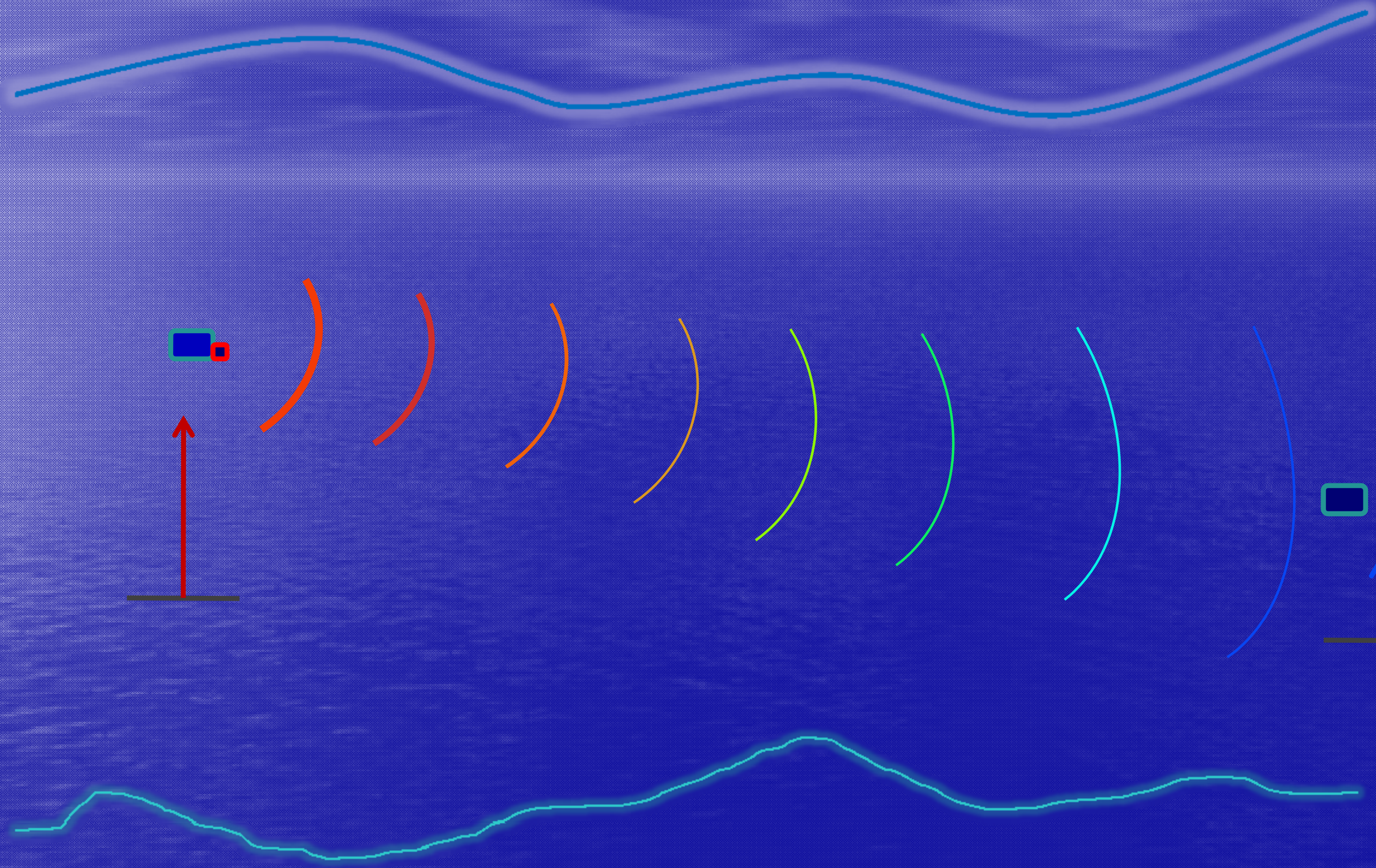
Acoustic Channel



Channel impulse response - multipaths

NetMar_{SyS}

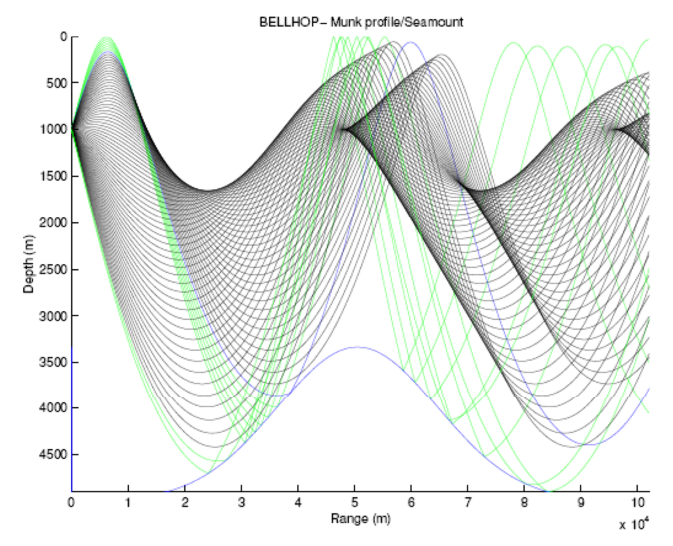
Acoustic Channel



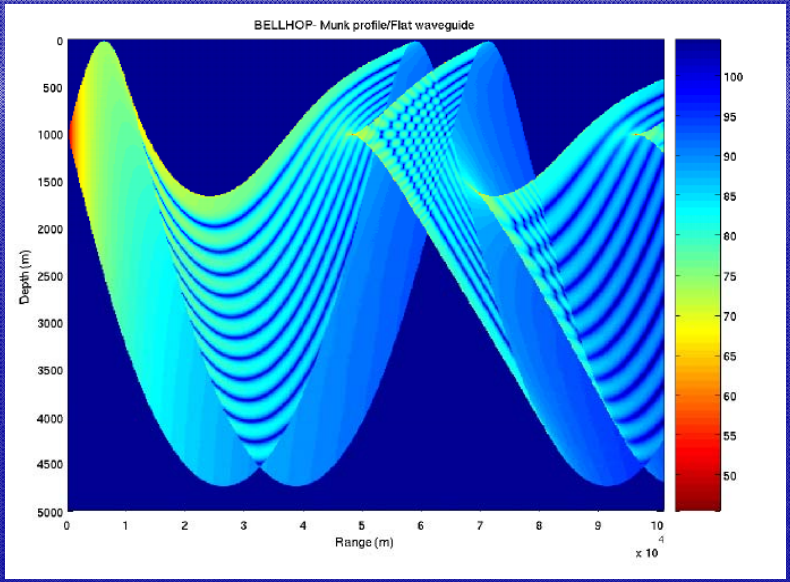
Power Losses – Spreading and Absorption

NetMar SyS

Acoustic channel



rays calculated in flat deep water waveguide



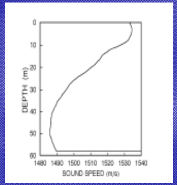
coherent transmission loss in deep water waveguide

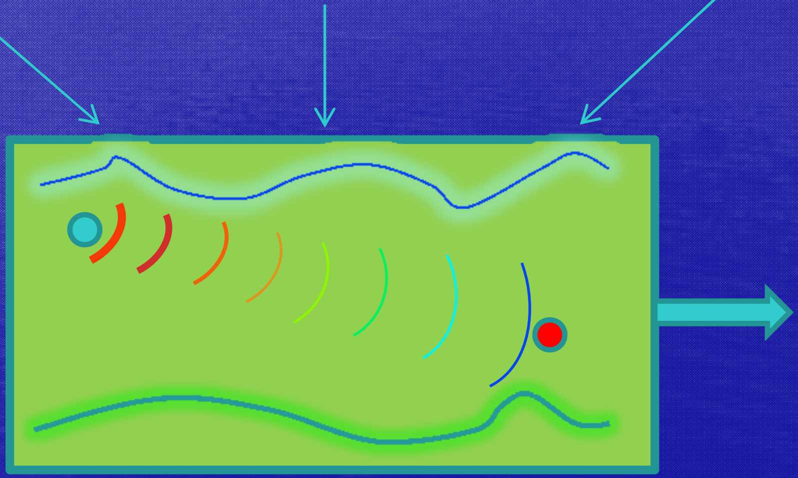
Transmission loss

NetMar SyS

BELLHOP ray tracing program

Acoustic channel simulation





Sea state

Seafloor characteristics

Sound speed profile

Emmiter

Receiver

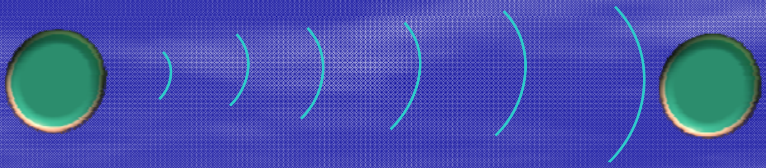
Frequency

Message received?

FUNCTIONALITY

NetMar_{SyS}

Acoustic channel simulation



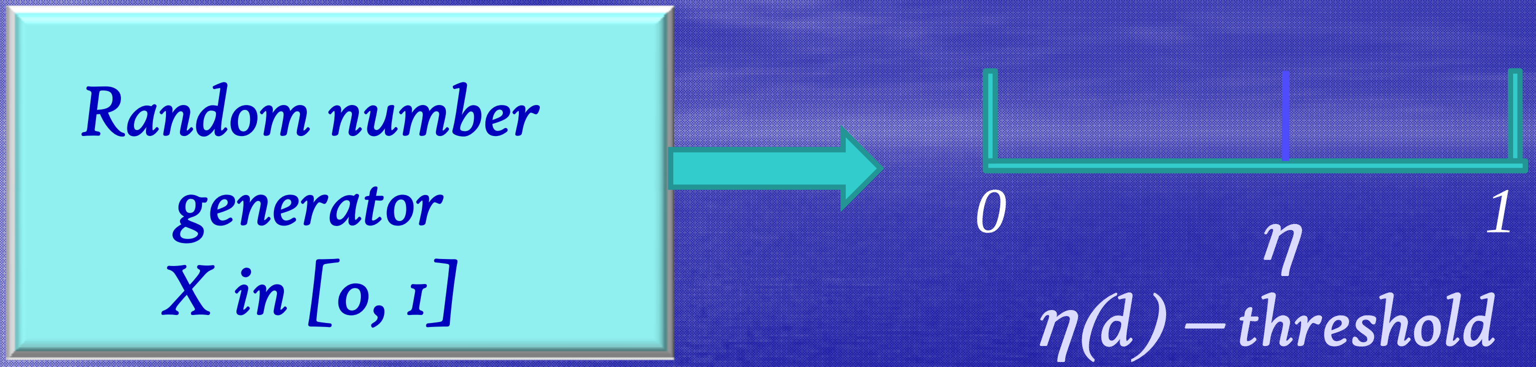
Random variable ξ

$$\xi = \begin{cases} 1, & \text{message received} \\ 0, & \text{message not received} \end{cases}$$

A simplified approach

NetMar$_{SyS}$

Acoustic channel simulation



Random number generator

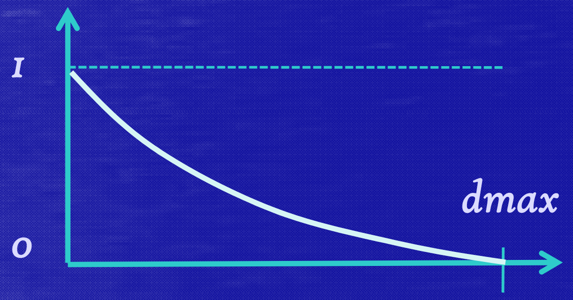
X in [0, 1]

$\eta(d)$ – threshold

$$\text{Prob}_{\xi=1} = \text{Prob } X > \eta$$

$$\text{Prob}_{\xi=0} = \text{Prob } X < \eta$$

$$\eta(d) = 1 - \exp\left[d/(d-d_{max})\right]$$



NetMar$_{SyS}$

Communication Constraints

- Is the matter THAT serious when it comes to COORDINATED PATH FOLLOWING?

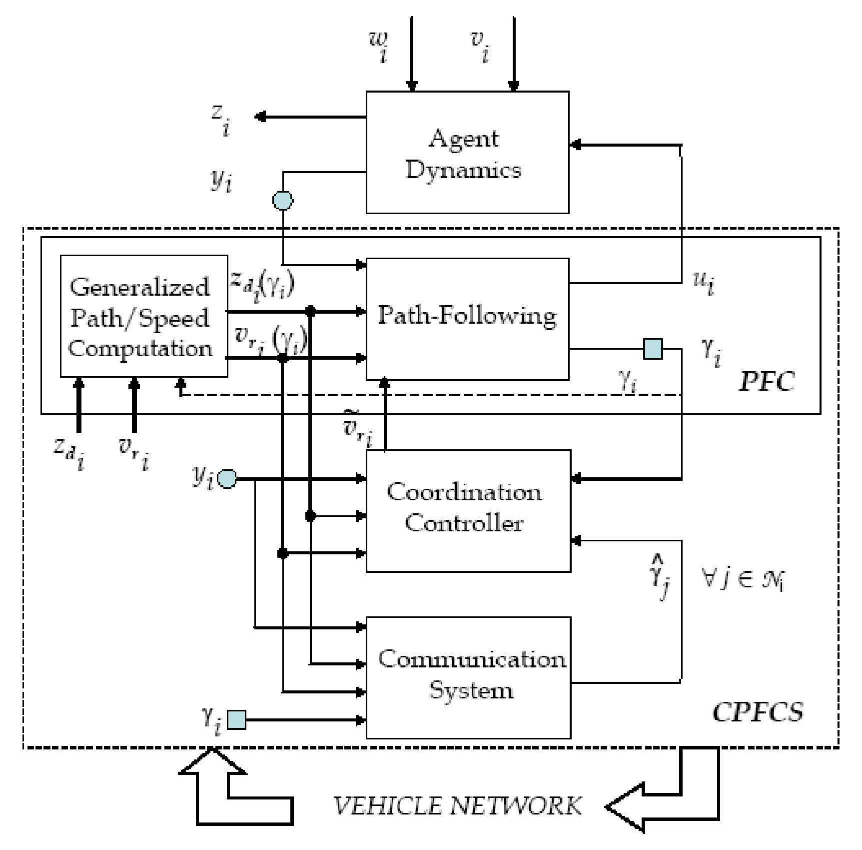
CHECK results on Networked Control

Two key references:

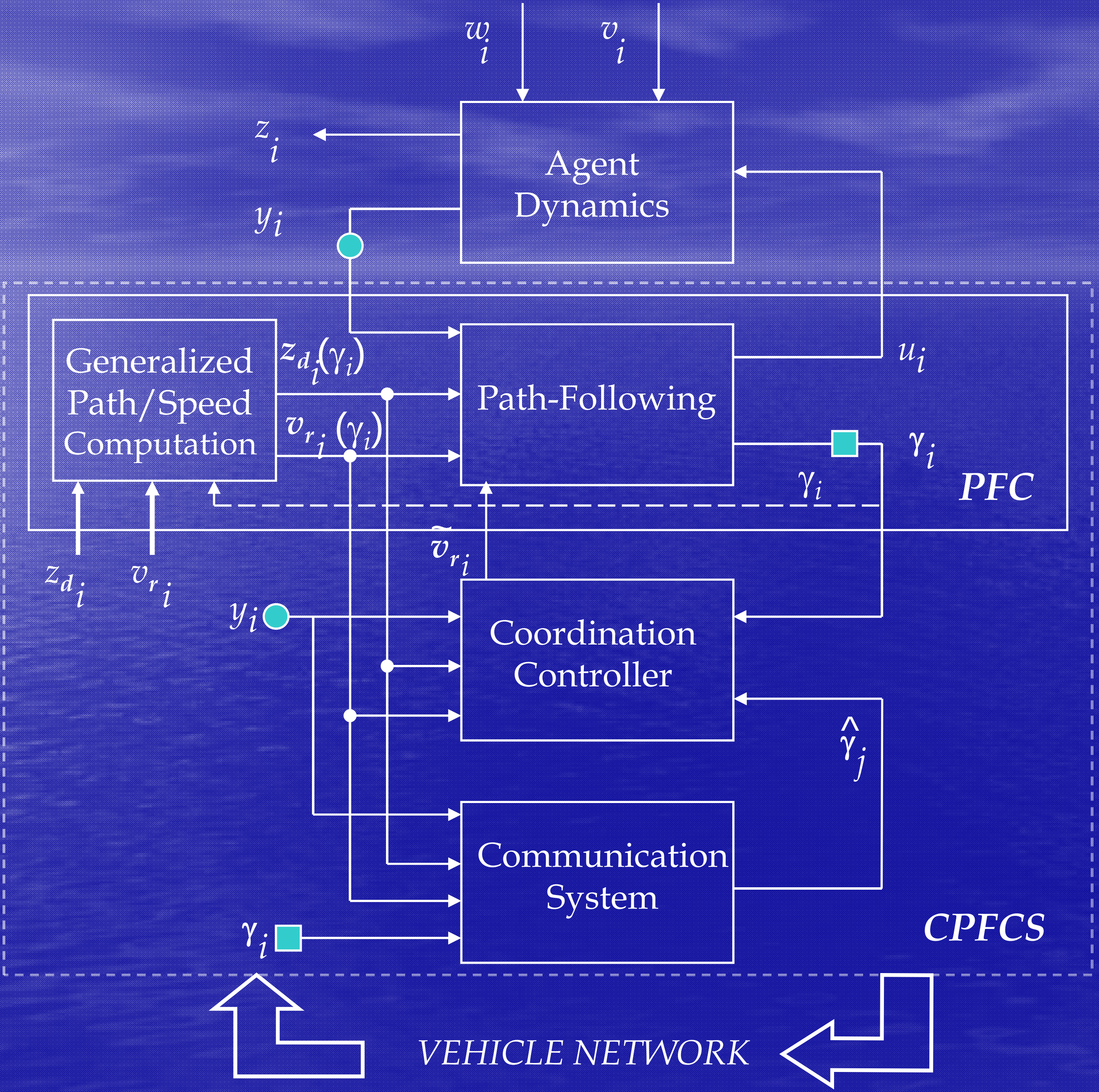
1. J. Yook et al., “Trading computation for bandwith: reducing communication in distributed control systems using state estimators,” IEEE Trans. Contr. Syst. Technology, Vol. 10, No. 4, 2002

2. Y. Xu and J. Hespanha, “Communication logic design and analysis for networked control systems,” in Current Trends in Nonlinear Systems and Control, Birkhauser, 2006.

A very general framework



A. Aguiar and A. Pascoal, "Coordinated Path-Following Control for Nonlinear Systems with Logic-Based Communication", submitted to CDC 2007.



w_i
v_i
z_i
Agent Dynamics
y_i
Generalized Path/Speed Computation
$z_{d_i}(\gamma_i)$
$v_{r_i}(\gamma_i)$
Path-Following
u_i
γ_i
γ_i
PFC
z_{d_i}
v_{r_i}
$\tilde{v}_{r_i}$
y_i
Coordination Controller
$\hat{\gamma}_j$
Communication System
γ_i
CPFCS
VEHICLE NETWORK

“Usual Trick”:

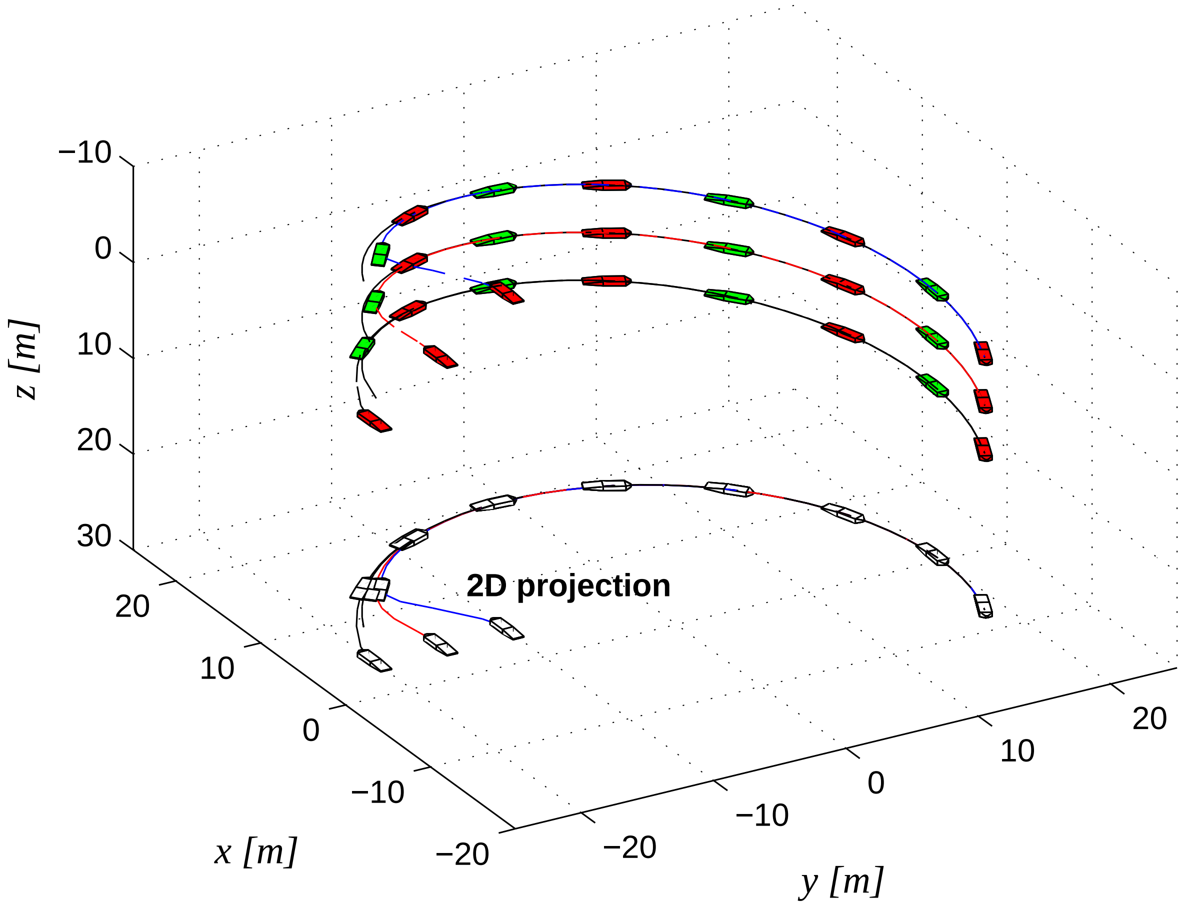
- Each and every agent runs estimates of the evolution of the path parameters of ALL agents it communicates with.

- *Intuition: agent i runs a model of what j “thinks i is “doing”*

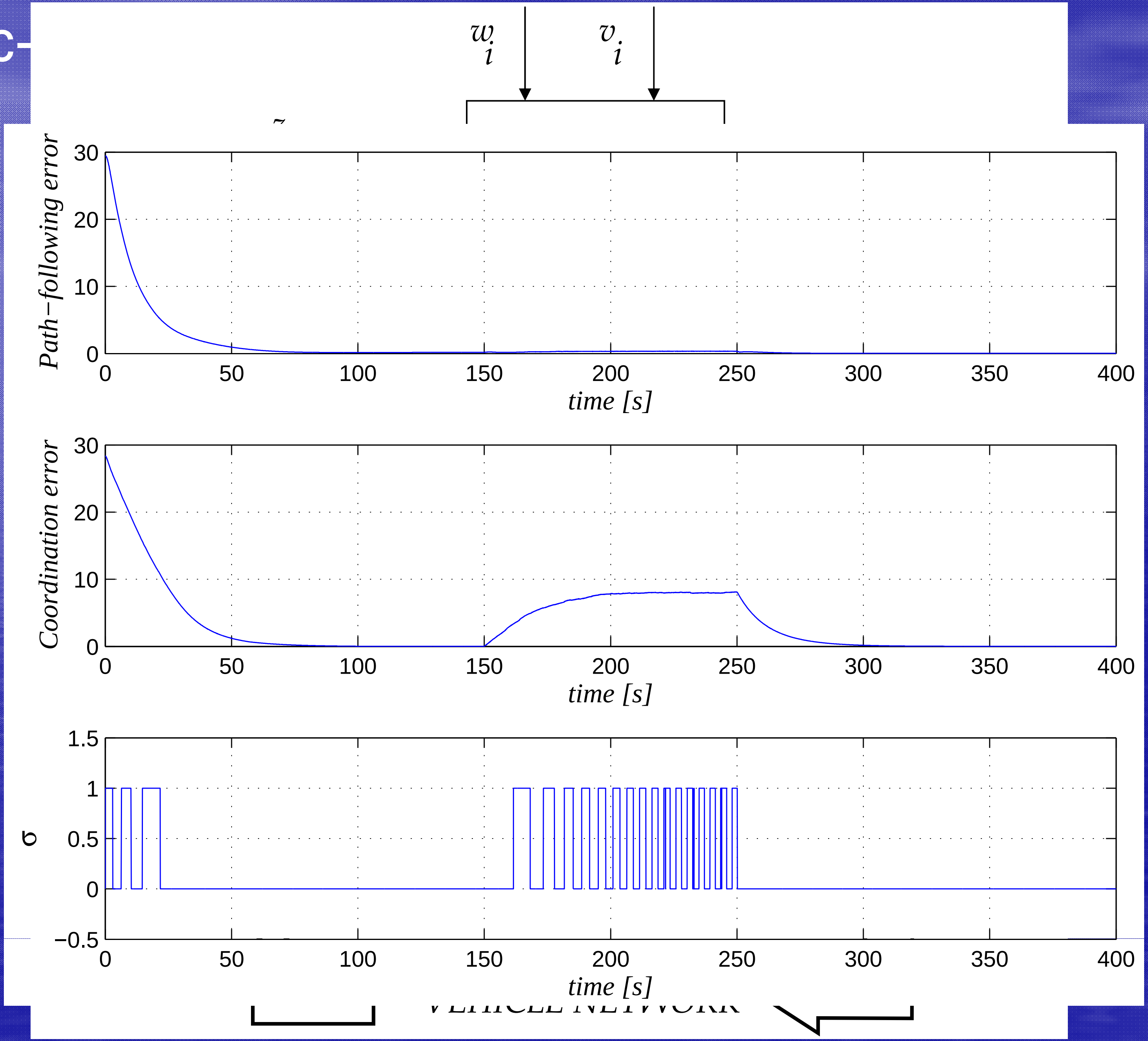
- When the prediction of state i and the actual value deviate “too much”, agent i broadcasts the measured information.

- *Each agent that receives info from i updates its estimator instantaneously.*

Logic-Based Communication



Logic-


w_i
v_i
Path−following error
30
20
10
0
0
50
100
150
200
250
300
350
400
time [s]
Coordination error
30
20
10
0
0
50
100
150
200
250
300
350
400
time [s]
σ
1.5
1
0.5
0
−0.5
0
50
100
150
200
250
300
350
400
time [s]
VEHICLE NETWORK

European Project IST 035223

Coordination and control of cooperating heterogeneous unmanned systems in uncertain environments

STREP project: 2006 – 2009

Jörg Kalwa

ATLAS ELEKTRONIK GmbH

António M. Pascoal

Institute for Systems and Robotics (ISR)
Instituto Superior Técnico (IST)

Workshop on Cooperative Objects in Buildings, Business, Industry and Critical Infrastructures, Lisbon, 25 June 2008

The vehicles

Delfim (IST/ISR)

ASTER^x (IFR)

Seawolf (ATL)

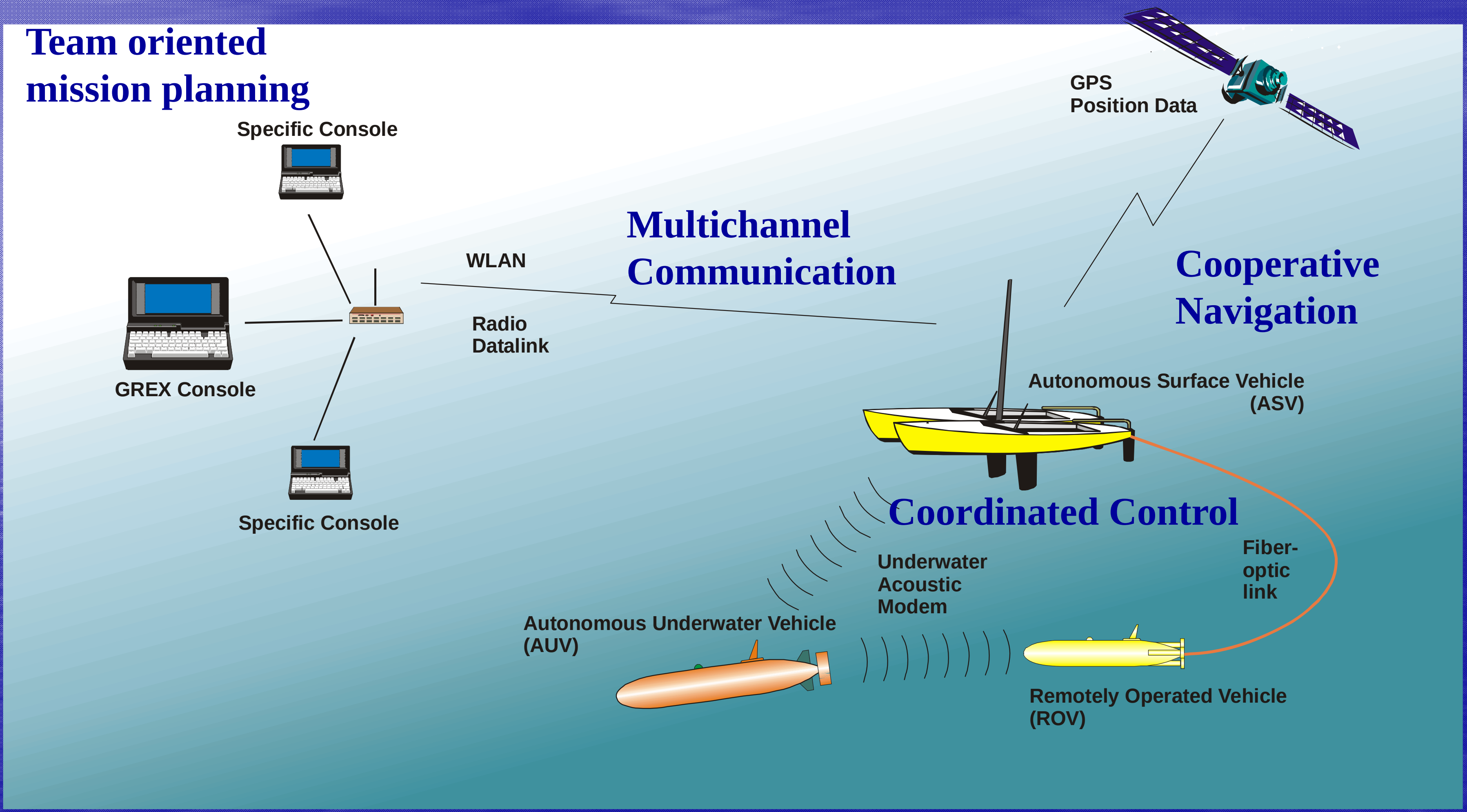
Arquipélago (IMAR)

Infante (IST/ISR)

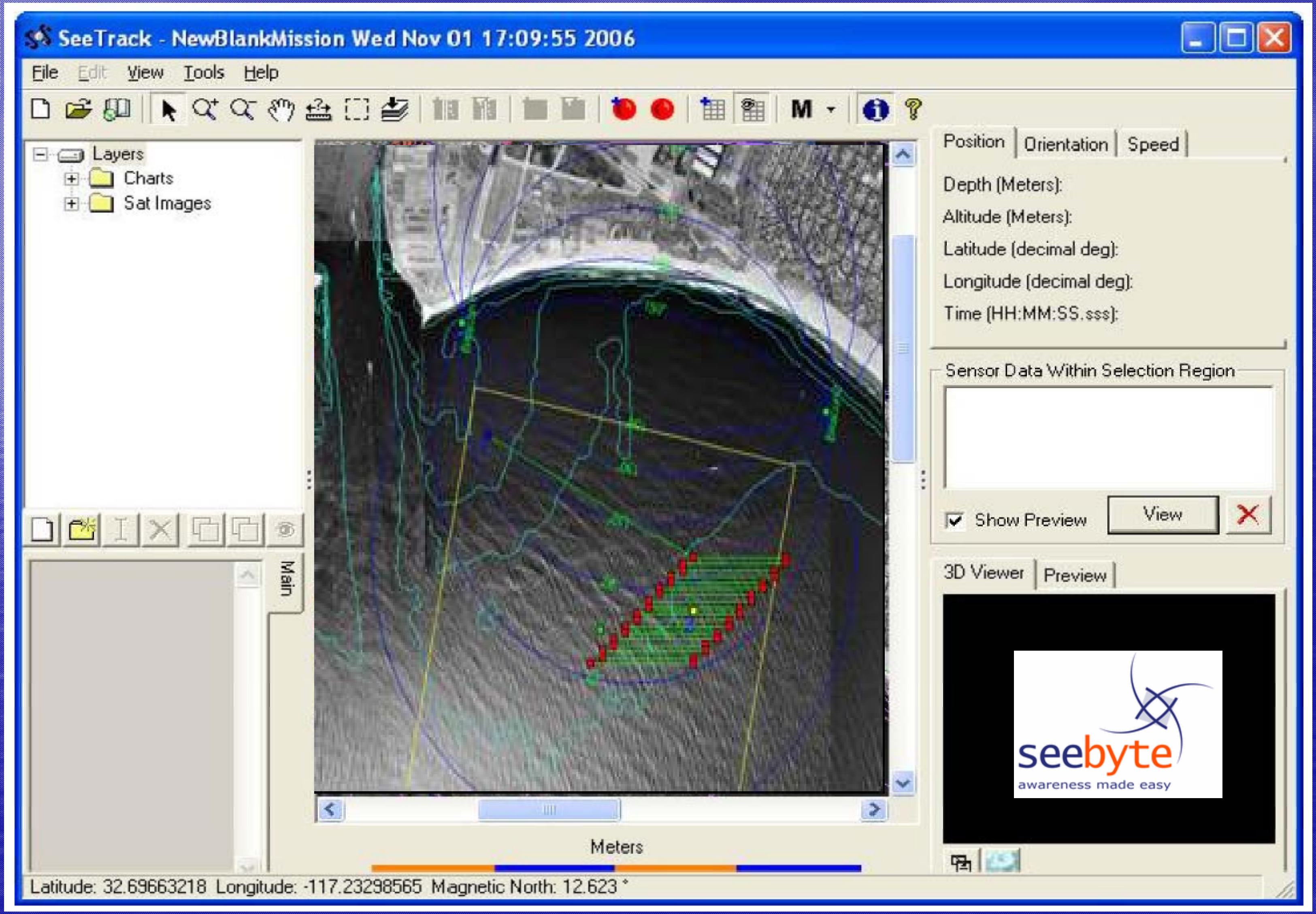
delfimx-20071025-p1040898.mo

MAYAShort.wmv

System Overview



SeeTrack Mission Planning GUI



SeeTrack - NewBlankMission Wed Nov 01 17:09:55 2006

Latitude: 32.69663218 Longitude: -117.23298565 Magnetic North: 12.623 °

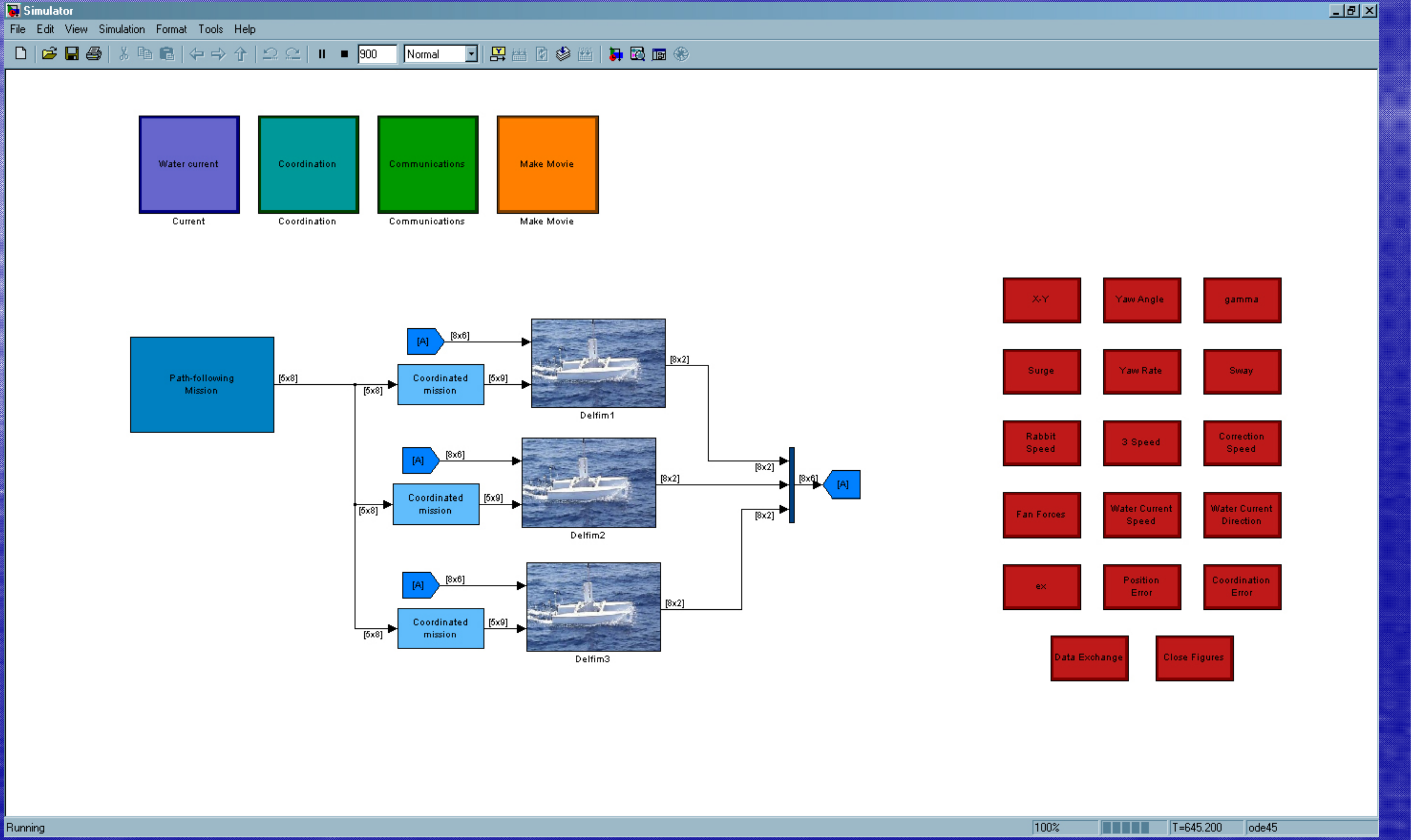
The Concept of Team-Oriented Mission Planning (TOMP)

GREX Meta-language Team Level

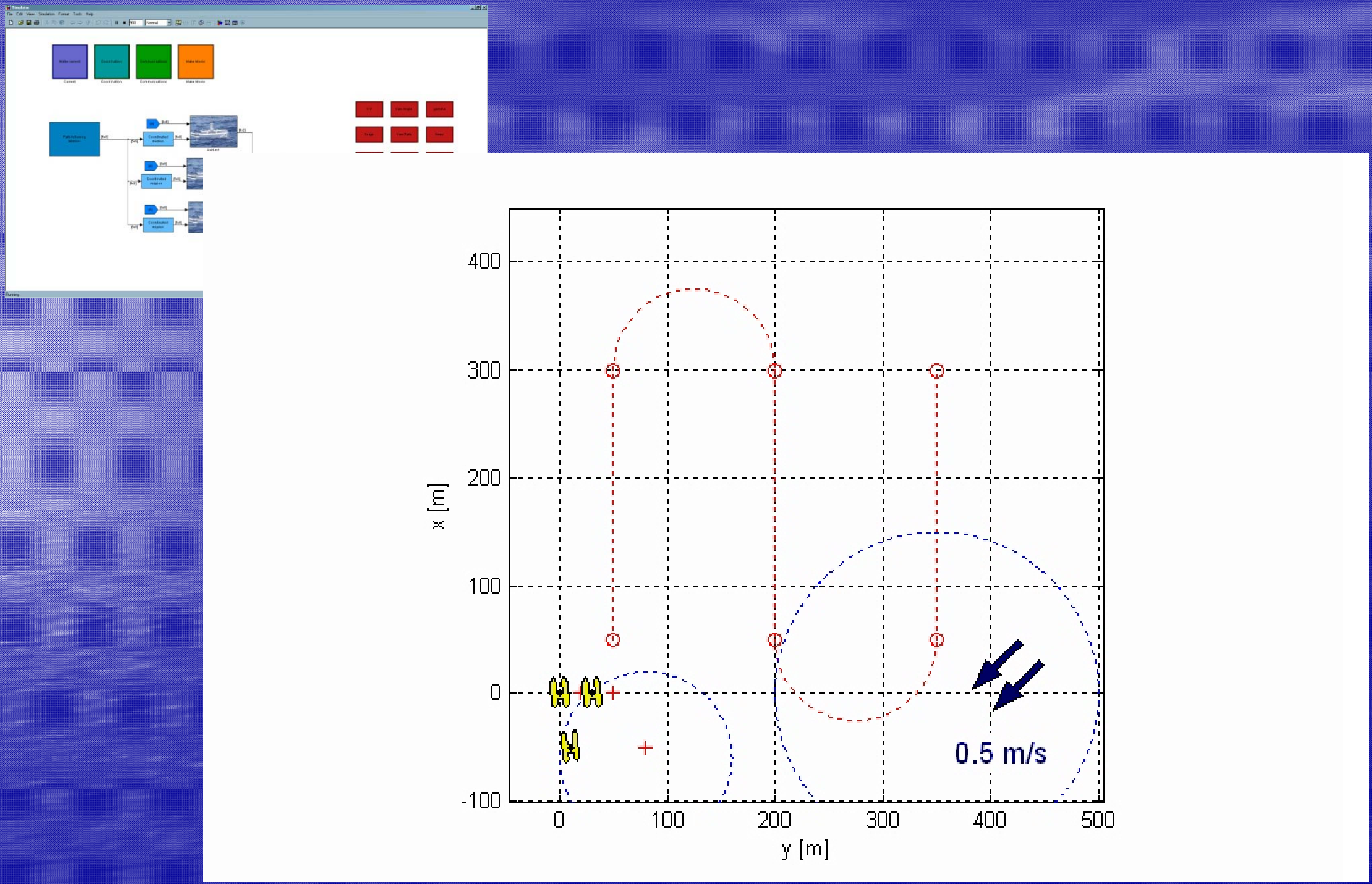
GREX Meta-language Vehicle Level

Languages of Real Vehicles

The Multiple Vehicle GREX simulator

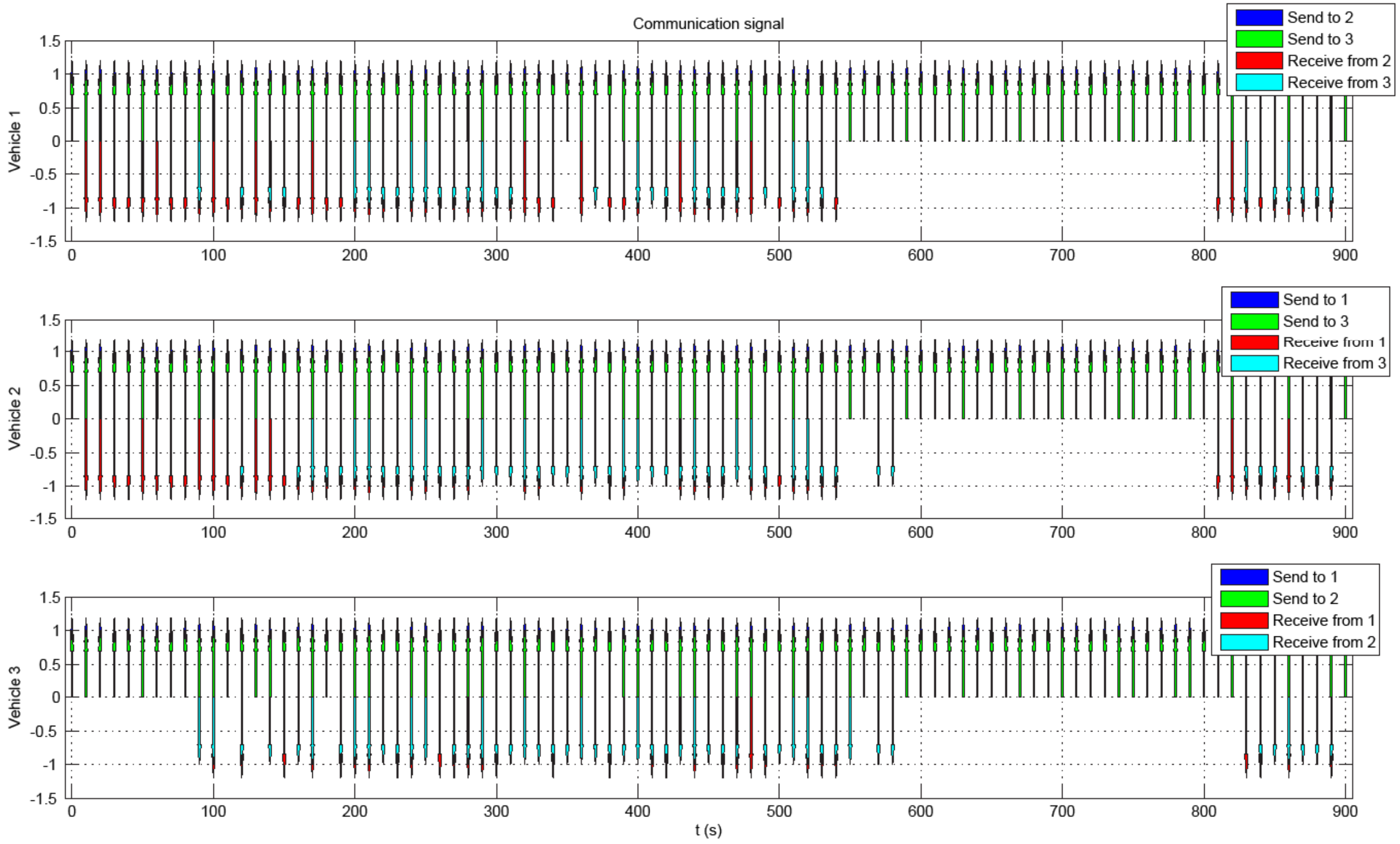


Running 100% T=645.200 ode45

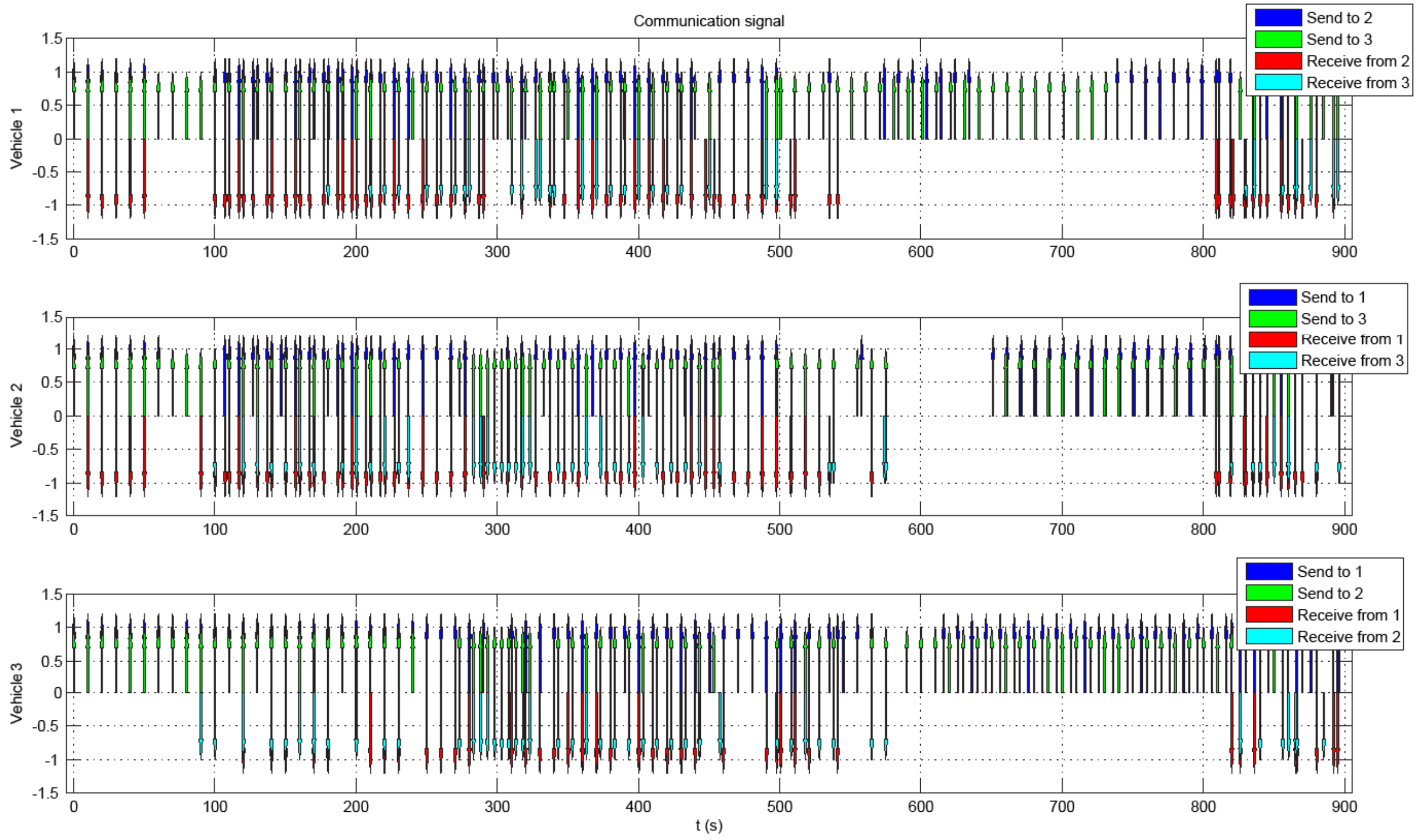


Communication Losses (“noisy areas”)

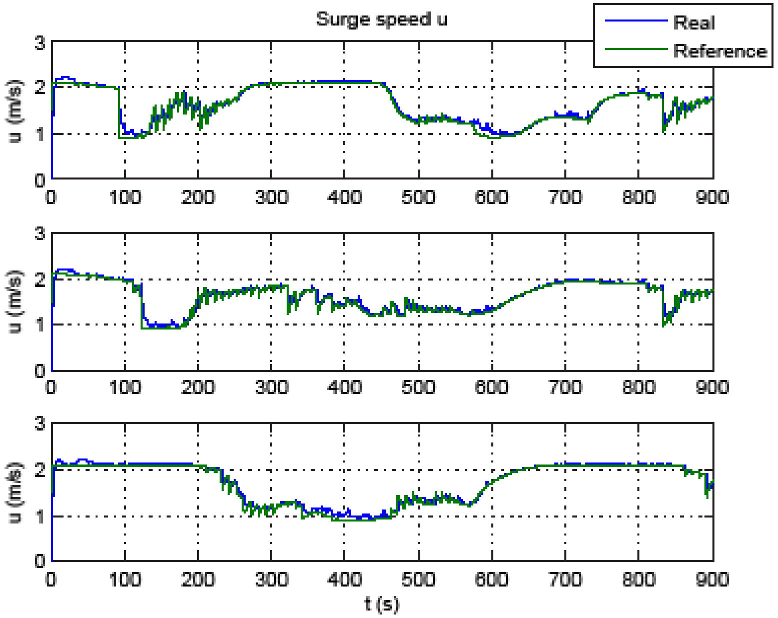
Data Exchange with Fixed Periodic Communication



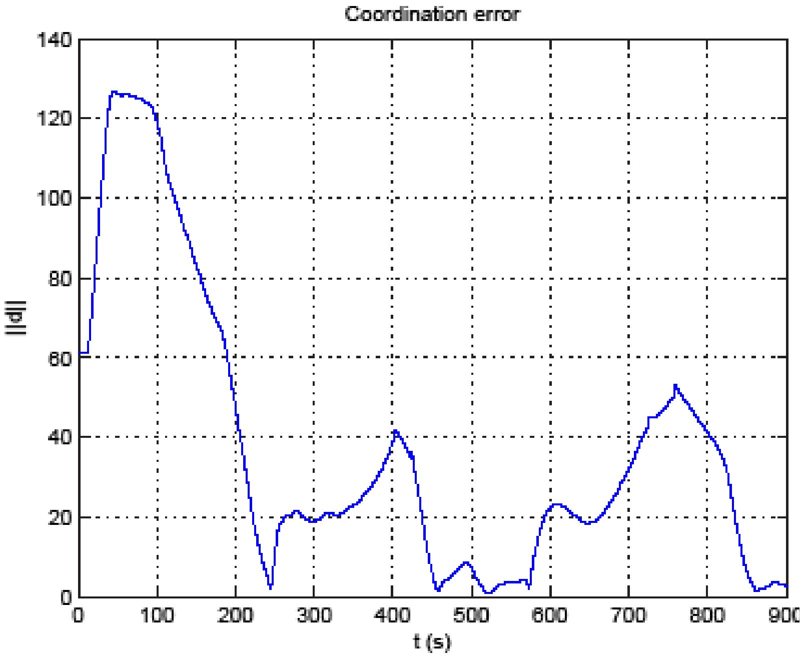
Data Exchange with Logic-Based Communication



Surge speed u



Coordination Error



Future Work

- State-dependent / multiple delays (*hard* *)
  (underwater comms: 1500 m/s).

- “Better model of communication losses

- **Coordinated Path Following** without expensive inertial units (bring in cooperative navigation).

- From concept to practice (Acoustic Dynamic Networking)

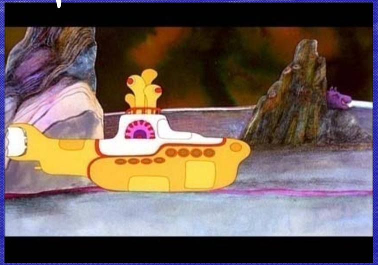
•Known delays - R. Ghabcheloo, A. Aguiar, A. Pascoal, C. Silvestre, “Synchronization in multi-agent systems with switching topologies and non-homogeneous communication delays ”, CDC 2007.

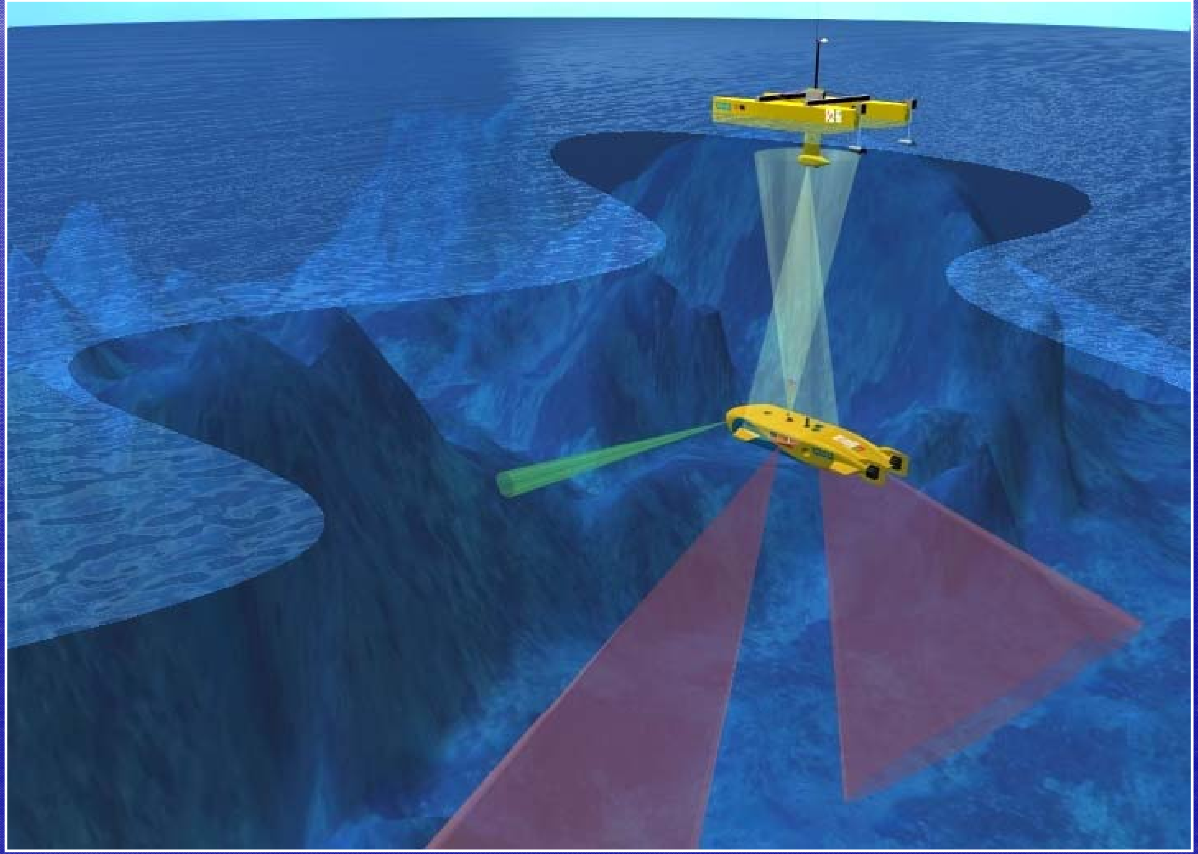
Beyond GREX (examples)

Cognitive Systems

Multiple Vehicle Coordination

Thank You!





IFAC Workshop, July 6, 2008