Coordination challenges in networked vehicle systems: are we missing something?

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Outline

- Developments in multi-vehicle systems at Porto University
- Some problems in multi-vehicle control
- What are we missing?
- Modelling challenges
- Control challenges
- Conclusions

DEVELOPMENTS IN MULTI-VEHICLE SYSTEMS AT U PORTO

LSTS-FEUP

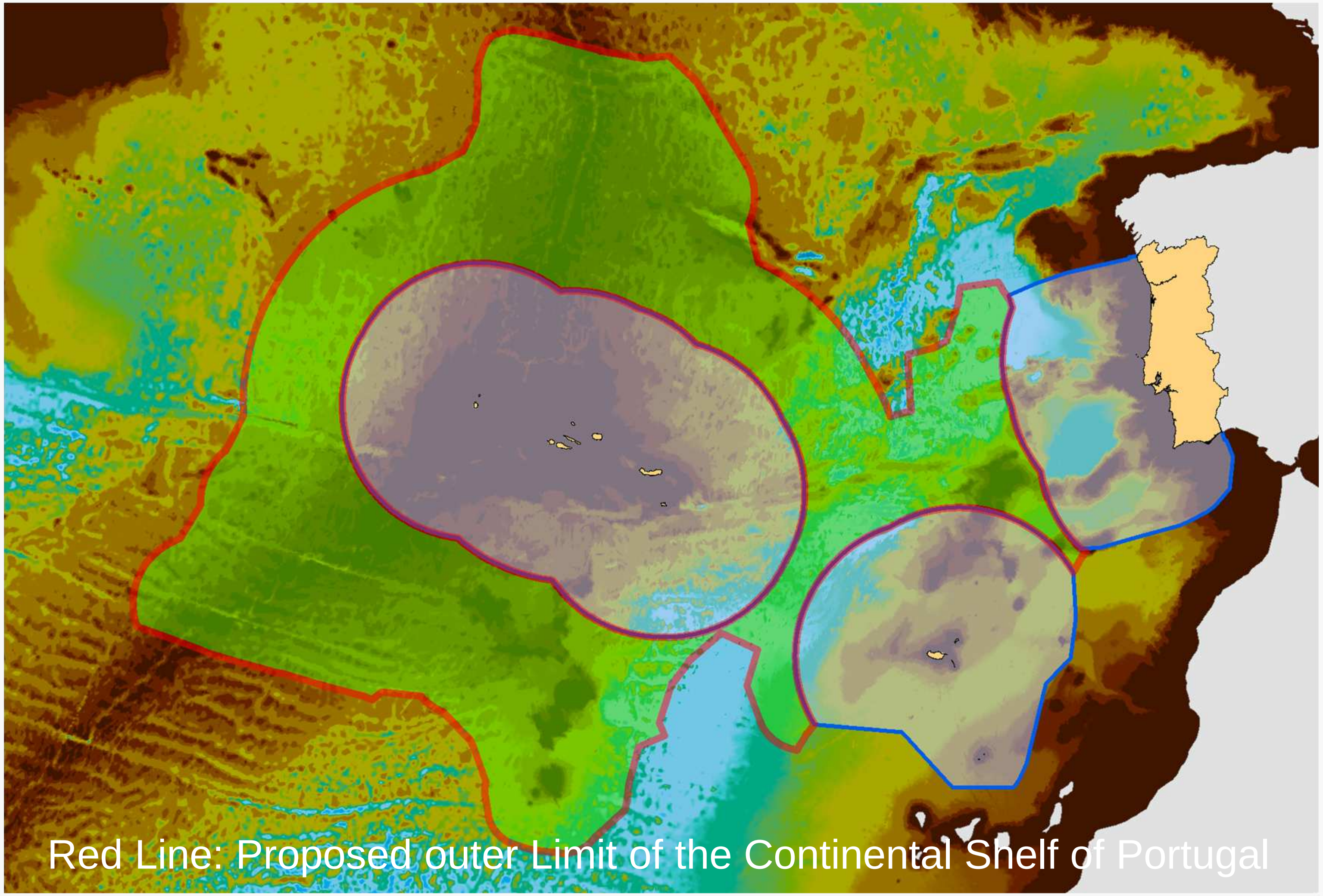
LABORATÓRIO DE SISTEMAS E TECNOLOGIA SUBAQUÁTICAS

UNMANNED VEHICLE SYSTEMS FOR A SUSTAINED PRESENCE IN THE OCEAN

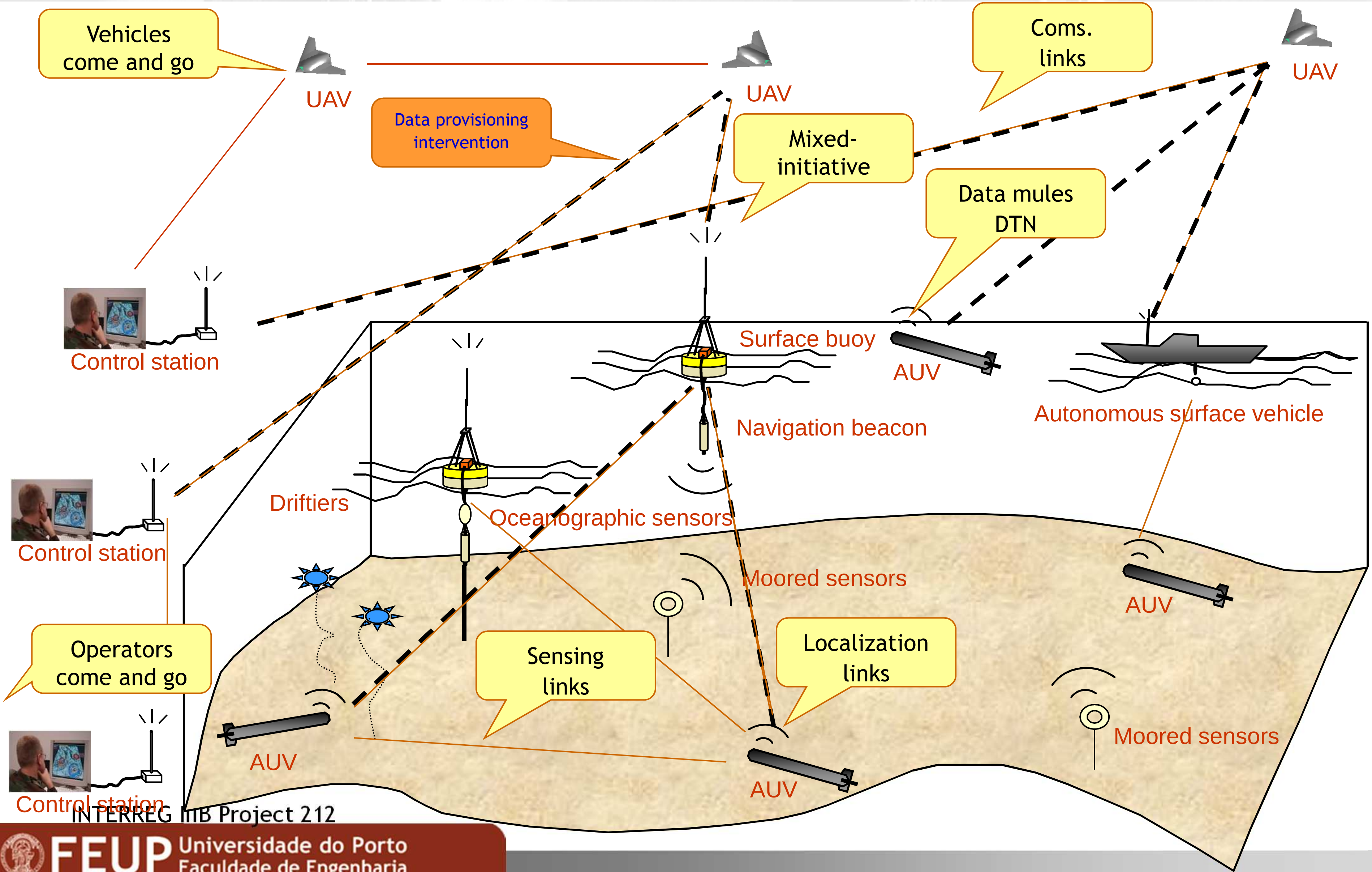
Mission: Design and deployment of innovative solutions for coastal oceanographic and environmental applications

NOPTILUS C4C SeaCon System PITVANT LSTS U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

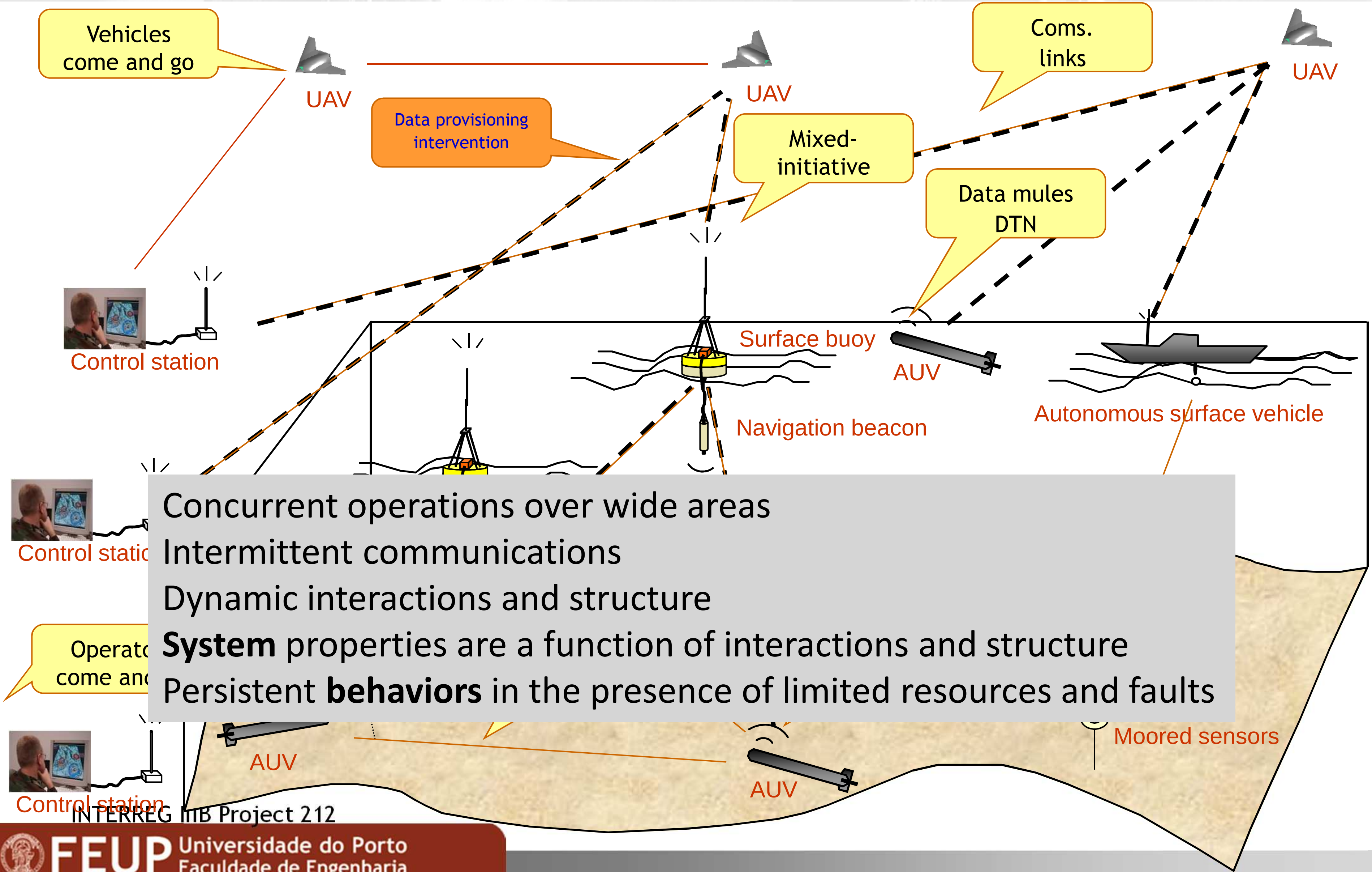
Extension of the continental shelf



Vision


Vehicles come and go
UAV
UAV
UAV
Data provisioning intervention
Coms. links
Mixed-initiative
Data mules DTN
Control station
Control station
Control station
Operators come and go
Surface buoy
AUV
Navigation beacon
Autonomous surface vehicle
Driftiers
Oceanographic sensors
Moored sensors
AUV
Sensing links
Localization links
Moored sensors
AUV
AUV

Vision



Concurrent operations over wide areas

Intermittent communications

Dynamic interactions and structure

System properties are a function of interactions and structure

Persistent **behaviors** in the presence of limited resources and faults

Ocean vehicles

Low cost vehicles
Common software/hardware platforms
Inter-operability frameworks

Air vehicles (Pitvant project with PO Air Force)

ANTEX-X02 (AFA)

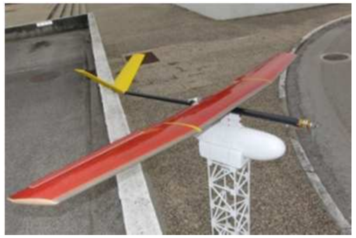
ANTEX-X03 (AFA)

ANTEX 02 Extended

Silver Fox

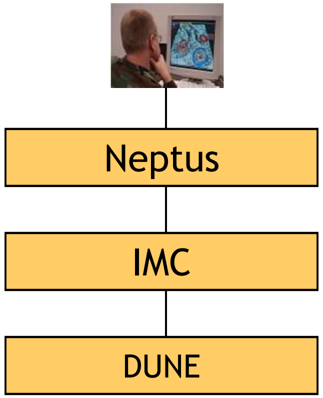
Flying Wing (AFA)

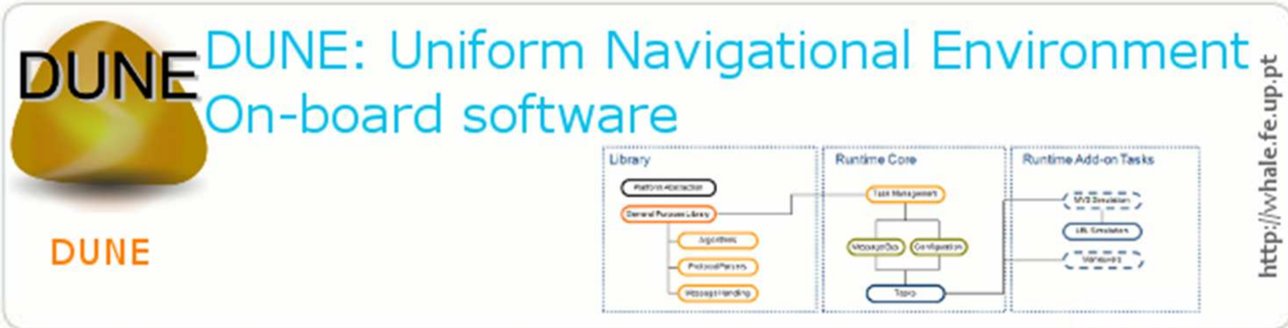
Low cost vehicles
Same software/hardware platforms
Inter-operability frameworks



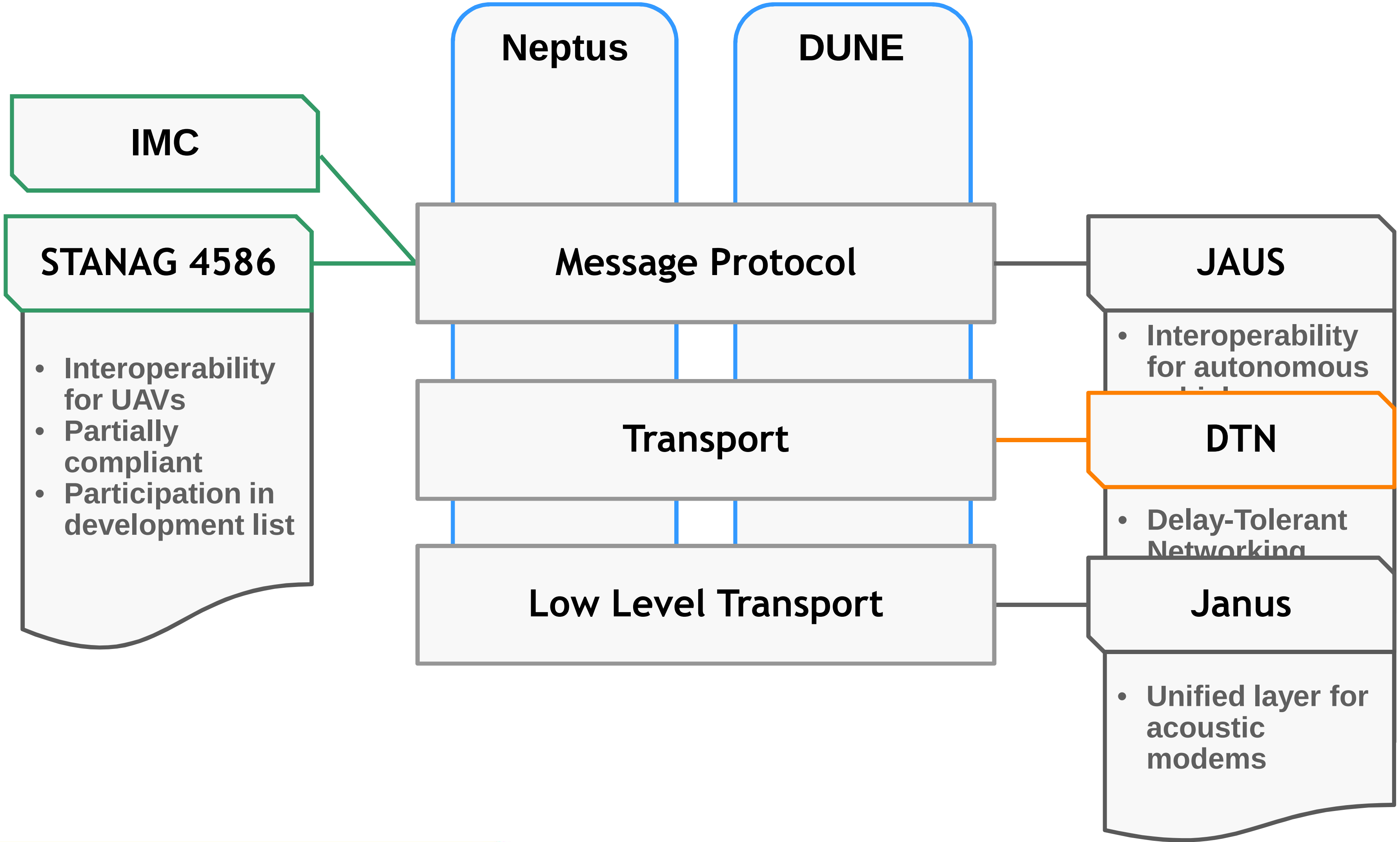
Mini UAV (AFA)

Software tool chain

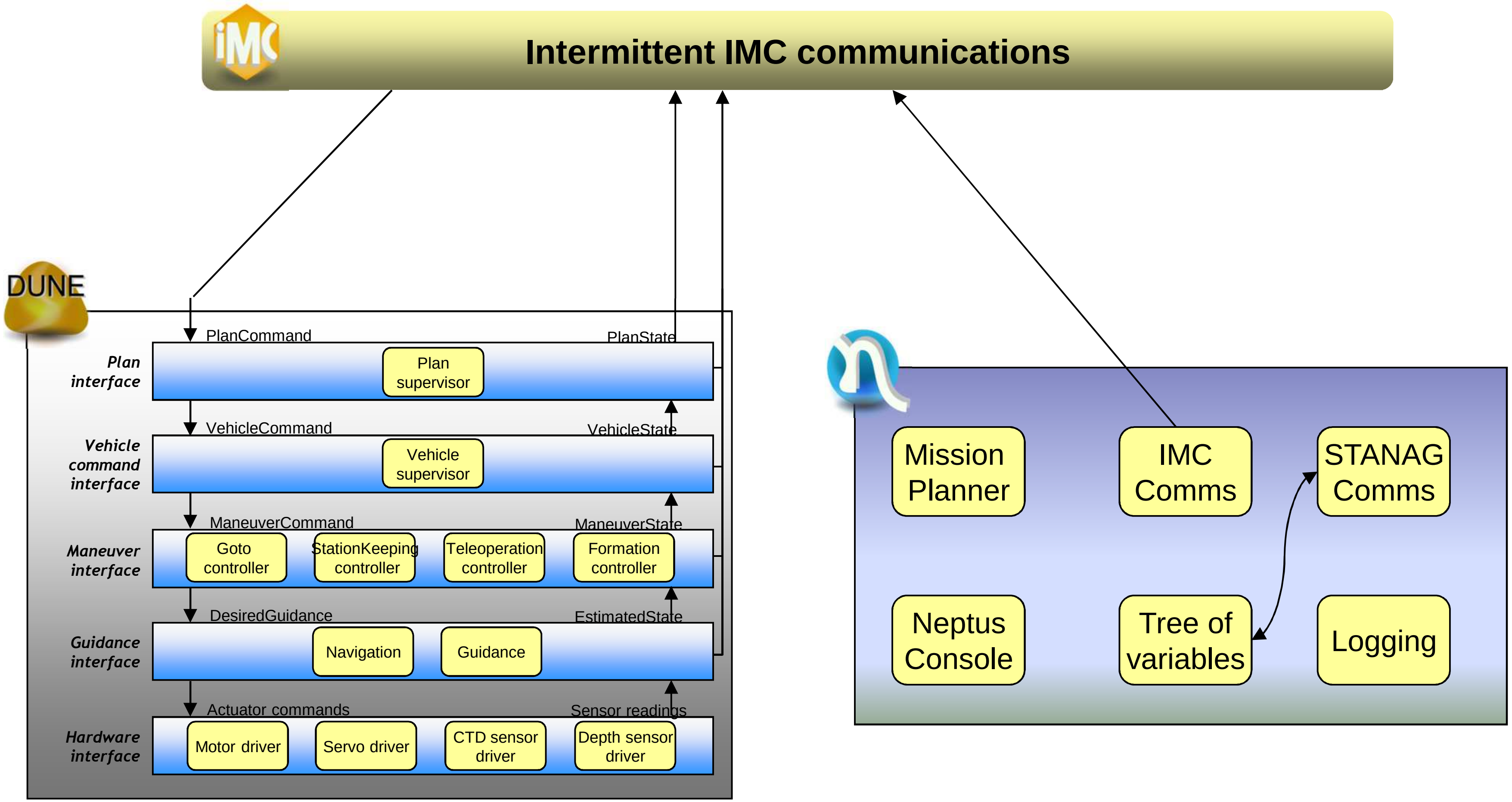




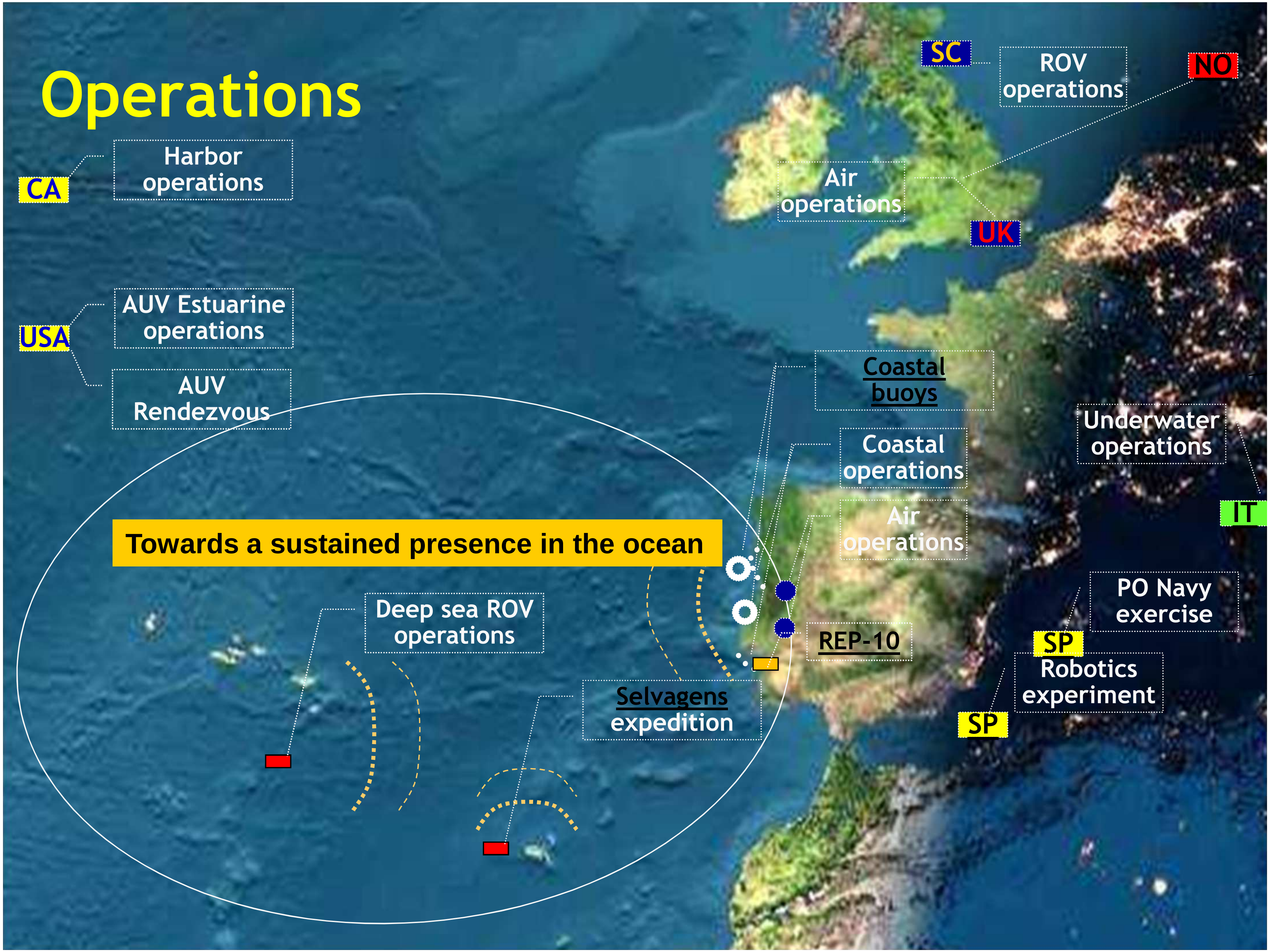
Layered communications architecture



Toolchain interaction

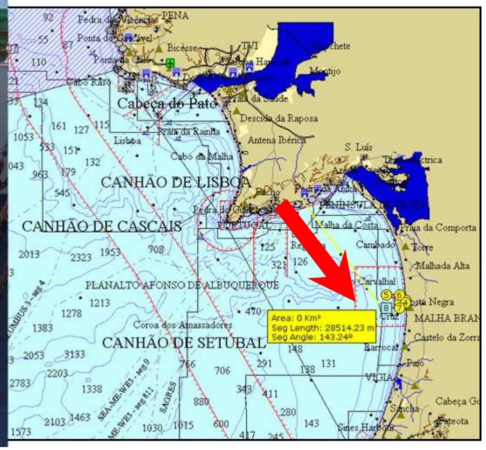


Operations

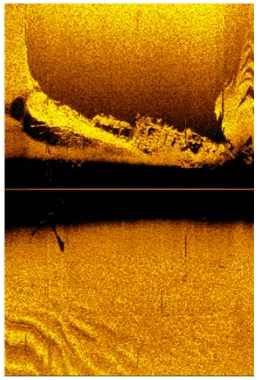

CA
Harbor operations
USA
AUV Estuarine operations
AUV Rendezvous
SC
ROV operations
NO
Air operations
UK
Coastal buoys
Coastal operations
Air operations
Underwater operations
IT
PO Navy exercise
SP
Robotics experiment
SP
REP-10
Towards a sustained presence in the ocean
Deep sea ROV operations
Selvagens expedition

REP10 exercise *July 2010*

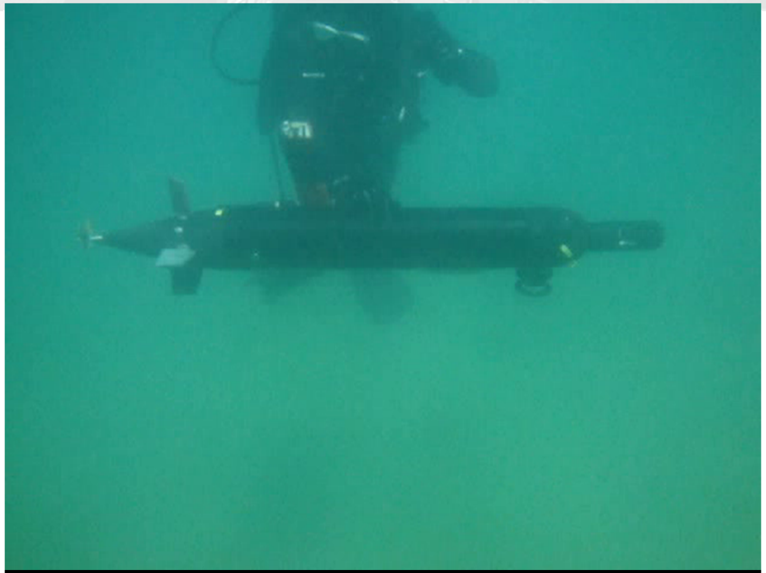
Cooperation
- Portuguese Navy (PO)
- NUWC (USA)
- Porto University (PO)
- NURC (NATO)

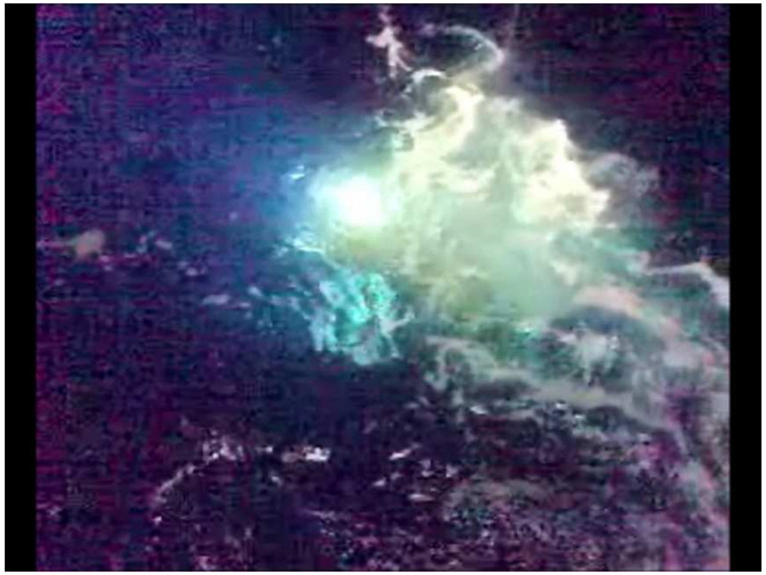


REP12 exercise *July 2012*



Ops with other ocean going vehicles





UAV Operations

Mini UAV

Night ops

Alfa X06

Extended

PREVIOUS STUDIES IN MULTI-VEHICLE CONTROL

DARPA-MICA

Task planning and execution for UAV teams

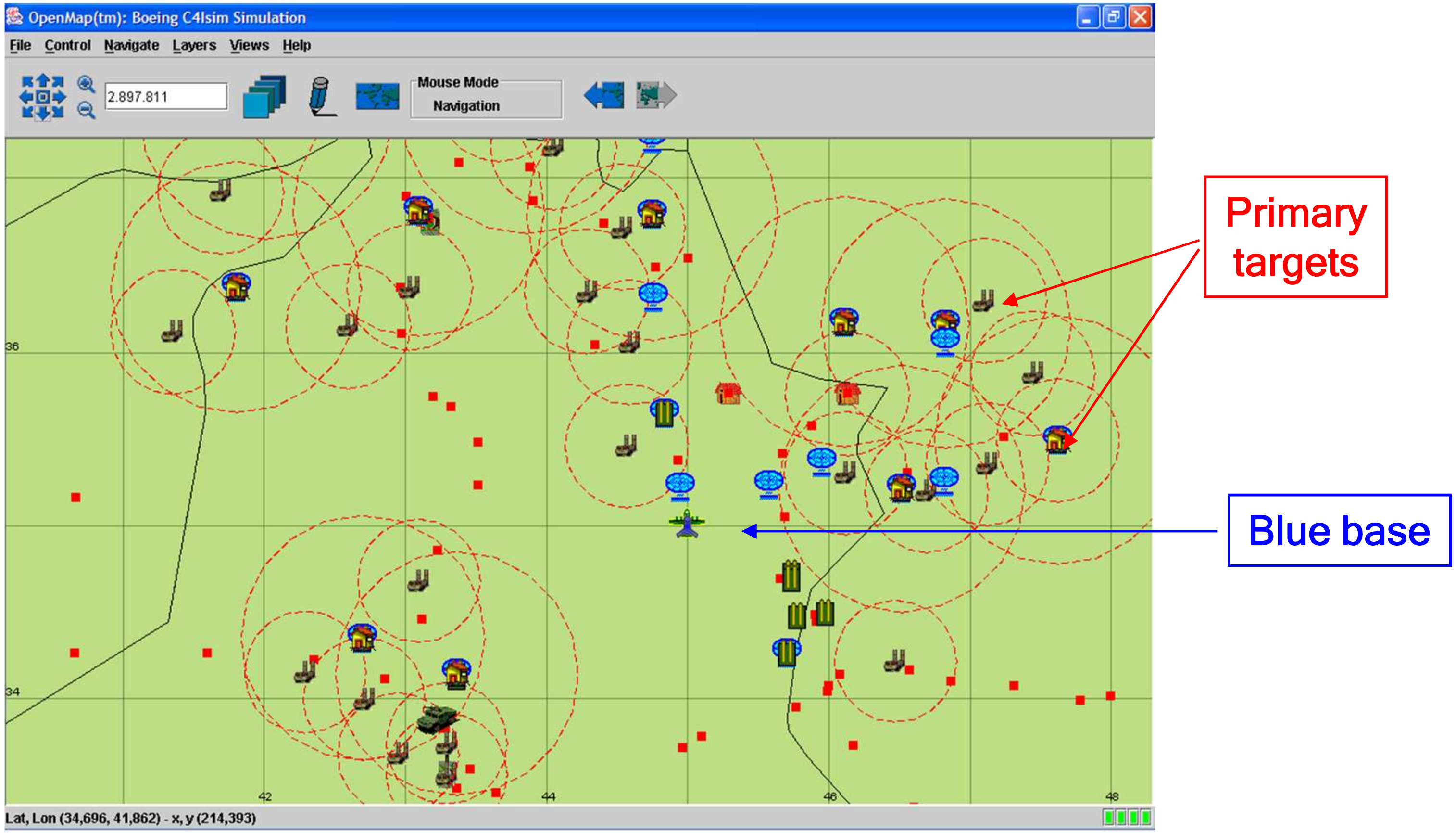
- João Sousa[*], Pravin Varaiya[+] and Tunc Simsek[+]
  - [*]Dept. Engenharia Electrotécnica e de Computadores
  - Universidade do Porto, Portugal
  - [+] Dept. of Electrical Engineering and Computer Sciences
  - University of California, Berkeley, CA 94720
  - {sousa, varaiya, simsek}@eecs.berkeley.edu

  - Research supported by Darpa Contract F33615-01-C-3150.

DARPA-MICA

Problem

- Design the attack of the Blue force of UAV against Red's ground force of SAM sites and radars.



J. Borges de Sousa, T. Simsek e P. Varaiya, "**Task planning and execution for UAV teams**", Proceedings of the Decision and Control Conference, Bahamas, 2004.

Threat function and path risk

- Instantaneous threat $r(x, y; P_{A,N}) =$

$$\sum_{j=1}^{k} \sum_{t} \sum_{N_{tj}=0}^{\infty} \sum_{n=1}^{N_{tj}} \left[\int_{A_j} f_t(|(x, y) - (x_n, y_n)|) |A_j|^{-1} dx_n dy_n \right] P(N_{tj})$$

$f_t(d)$ is the instantaneous threat posed at a distance d from target if type d

The integral is the expected value of this threat

- Risk faced by a UAV flying at speed $v > 0$ along a path γ from $\gamma(0)$ to a destination $\gamma(\tau)$ facing threat $P_{A,N}$

$$\rho(\gamma; P_{A,N}) = \int_{\sigma=0}^{\tau} r(\gamma(\sigma); P_{A,N}) \frac{d\sigma}{v},$$

- Value function for threat $P_{A,N}$ with $\gamma(\tau) = (\bar{x}, \bar{y})$

$$V((\bar{x}, \bar{y}); P_{A,N}) = \min_{\gamma} \rho(\gamma; P_{A,N})$$

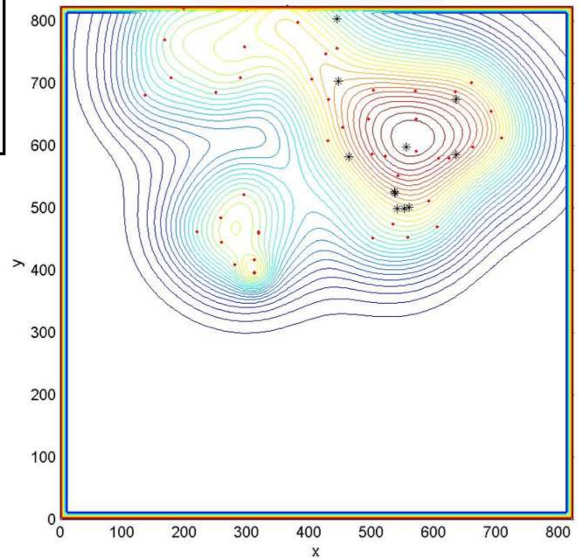
Initial situation

IPB

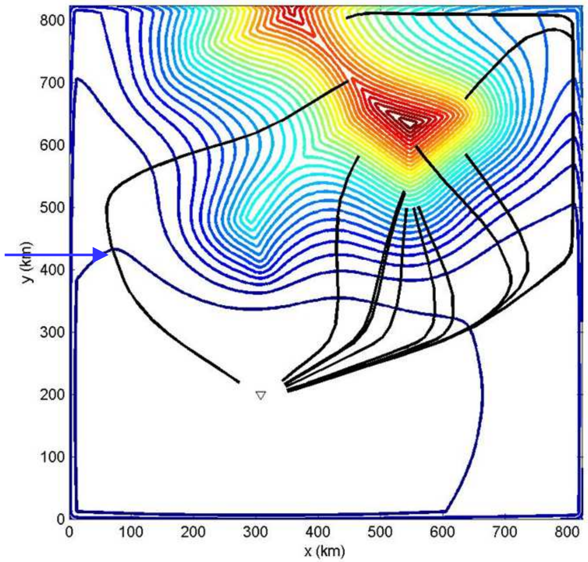
- Resoluti… km
- Number of threats: 91
- Primary targets =
  {EW1-6,TEL1-4, TELS1-2}

Idea: Phased operation waves

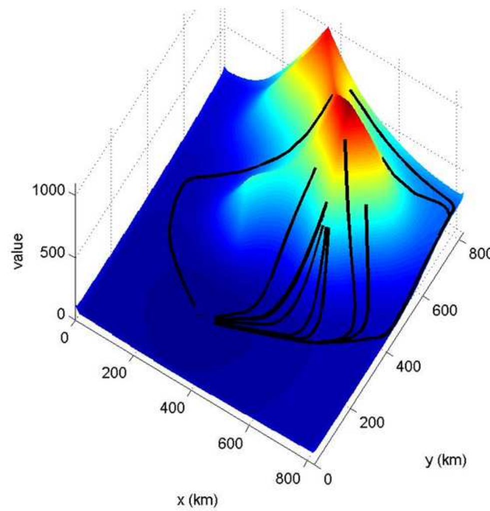
Threat function



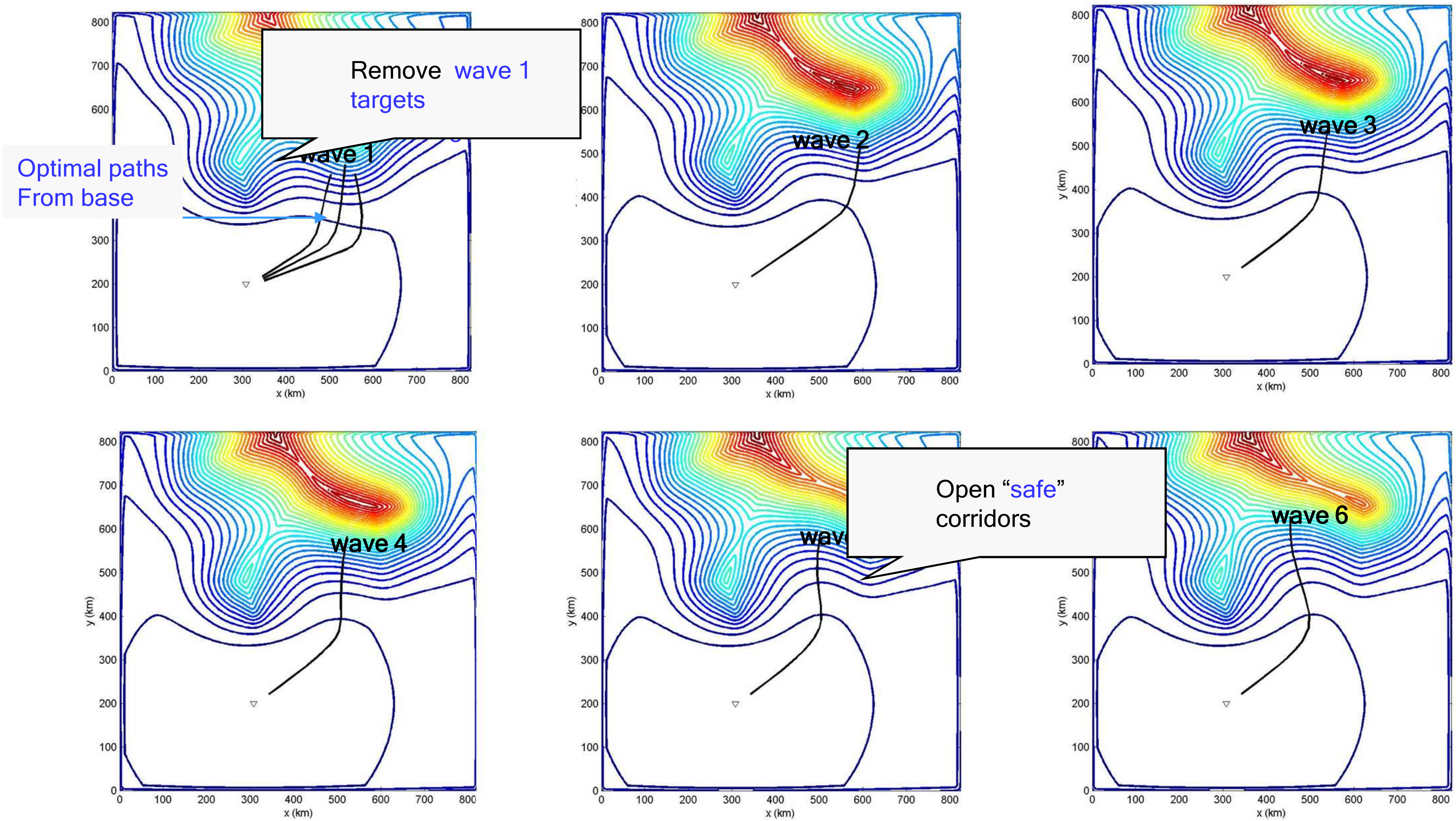
Value function



Minimum risk paths to primary targets

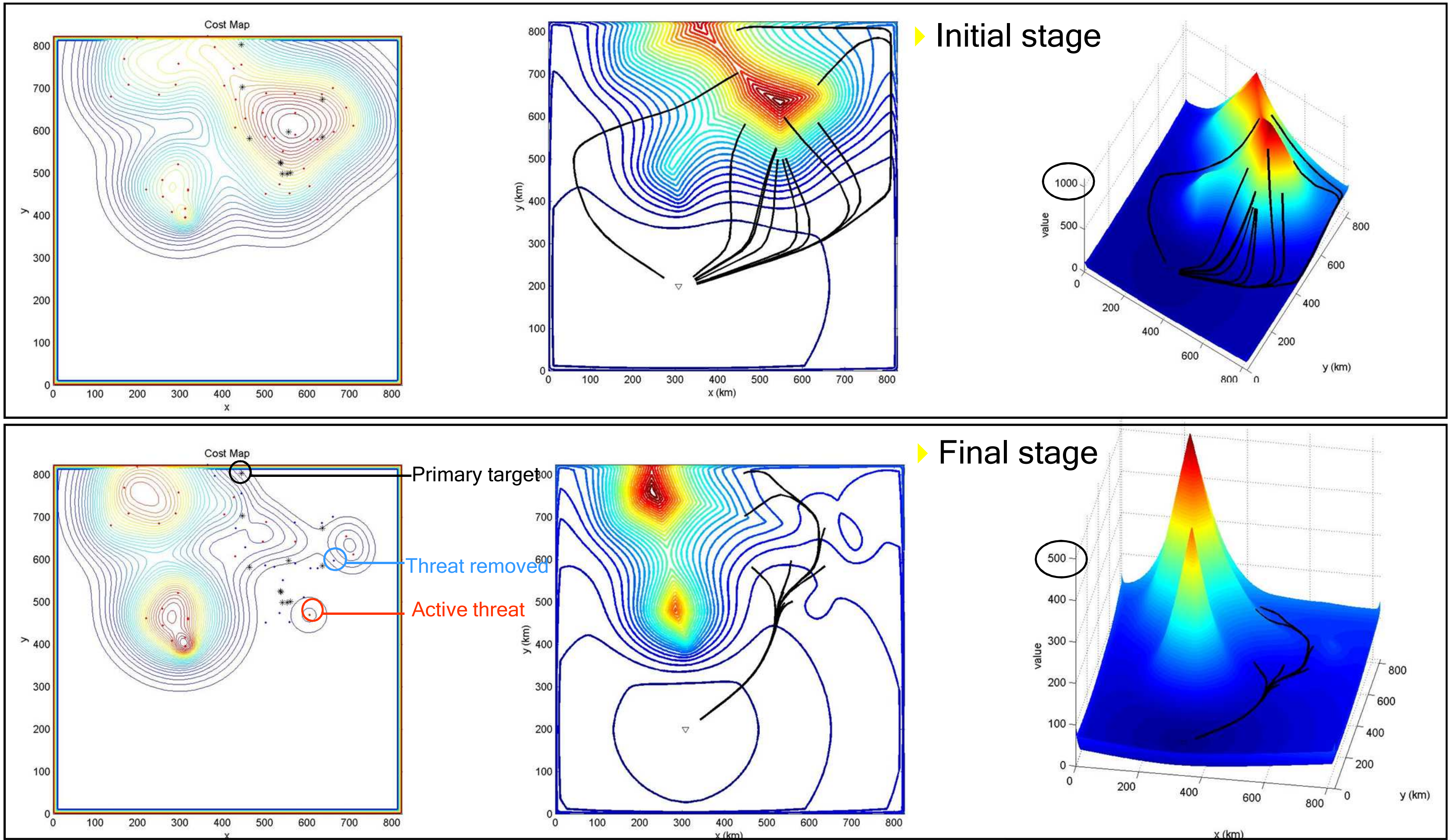


Operator assisted procedure

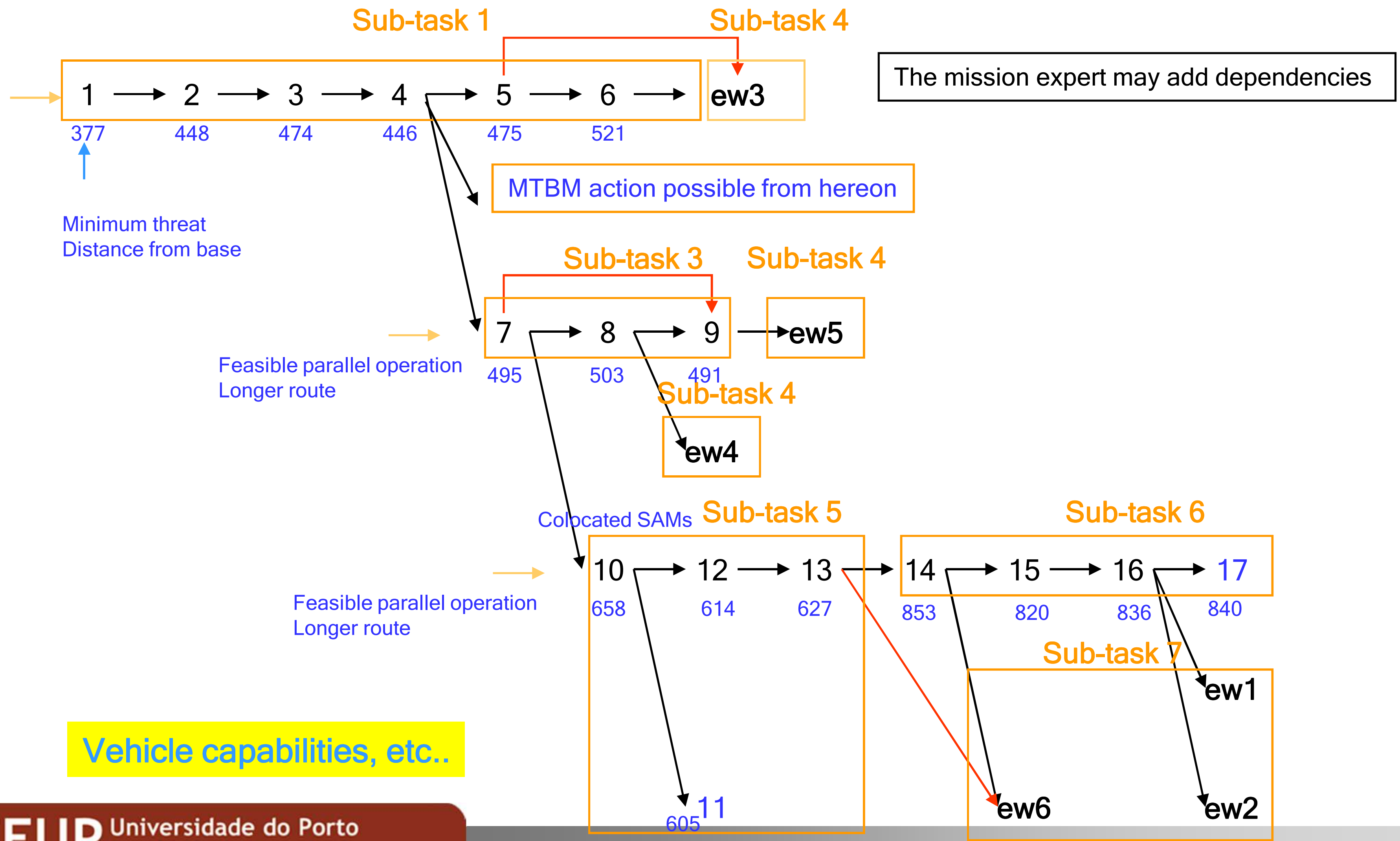


Initial stage versus final stage

$$i = N$$



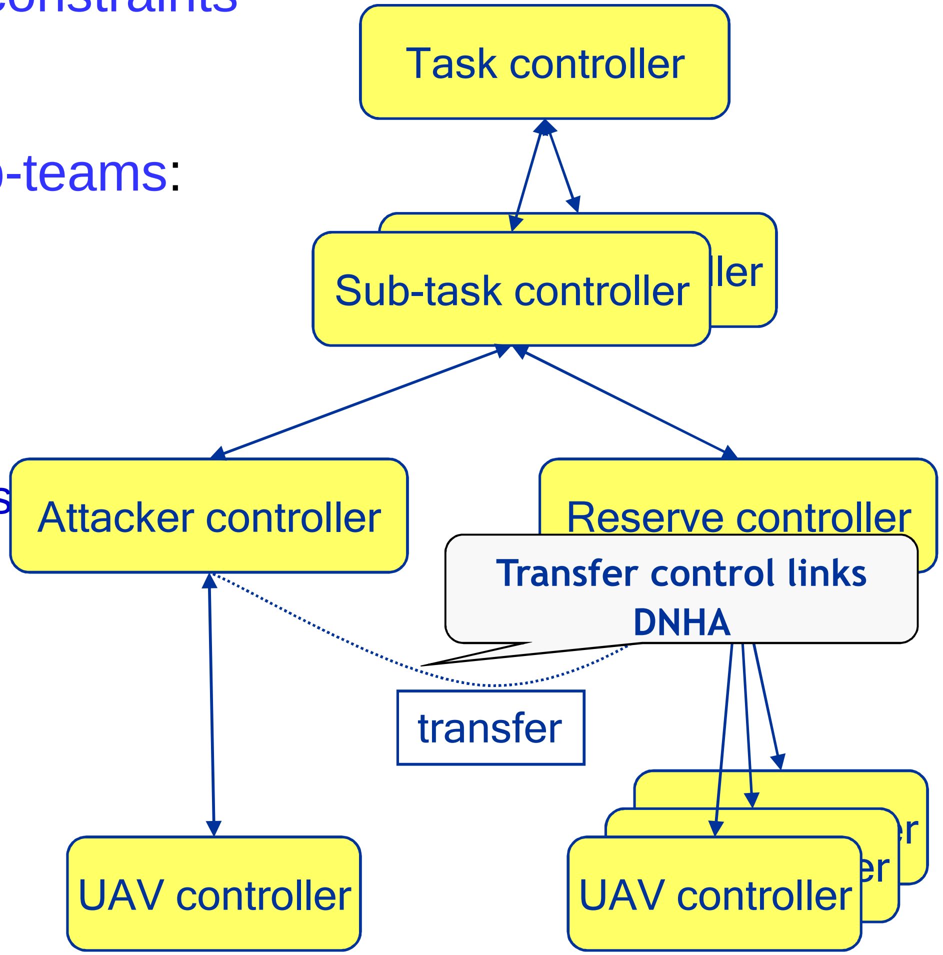
Plan: tasks + subtasks



Vehicle capabilities, etc..

Execution strategy and controllers

- Task = n sub-tasks + precedence constraints
- One team per sub-task
- Each team is organized as two sub-teams:
  - Attacker
  - Reserve
- Attacker
  - Opens corridor
  - Satisfy task precedence constraints
  - Keep executing legs until
    - Sub-task terminates
    - Eliminated or out of assets
- Reserve
  - Advance while is safe
  - Replace attackers



A verified hierarchical control architecture for coordinated multi-vehicle operations

João Tasso Borges Sousa*, Karl Henrik Johansson**

Jorge Estrela da Silva*** Alberto Speranzon**,

* Faculdade de Engenharia da Universidade do Porto - Portugal

** Royal Institute of Technology - Sweden

*** Instituto Superior de Engenharia do Porto - Portugal

Universidade do Porto
Faculdade de Engenharia
FEUP

KTH
VETENSKAP OCH KONST

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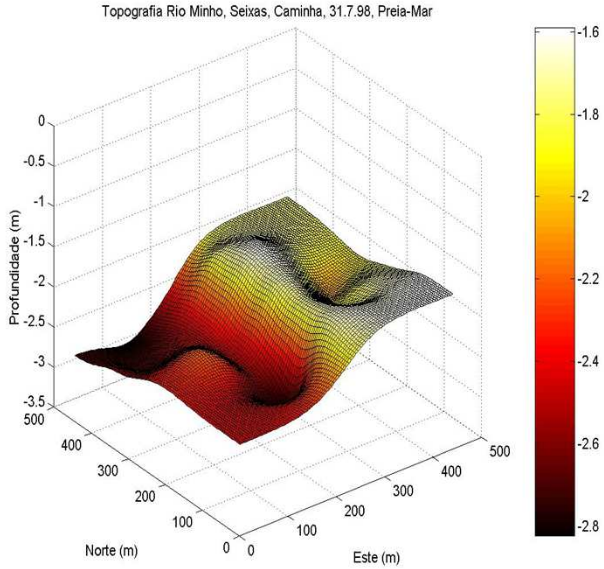
Multi-vehicle search problem

- Vehicles v_i
  - $V = \{v_1, \ldots, v_n\}$
  - Each vehicle v_i
    - Limited communication capabilities: bandwidth and range
    - Sensor for local measurements
    - Onboard computer for coordination and control



- Scalar field
  - $v = f(x,y,z,t)$

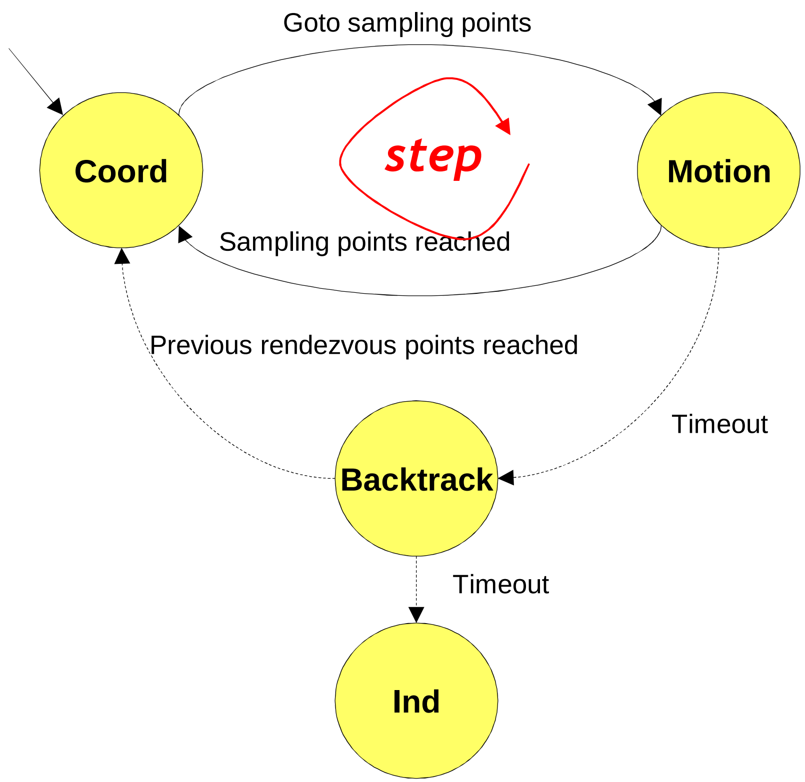
- Search algorithm
  - Repeat until termination
    - Calculate next sampling points
    - Go to sampling points

João Borges de Sousa, Karl H. Johansson, Jorge Silva and Alberto Speranzon, "A verified hierarchical control architecture for co-ordinated multi-vehicle operations", Int. J. Adapt. Control Signal Process. 2006.

Problem

- Given
  - Set of initial locations I
  - Measurement function m
  - Way-point generation function g
  - Termination criteria c
  - Specification S

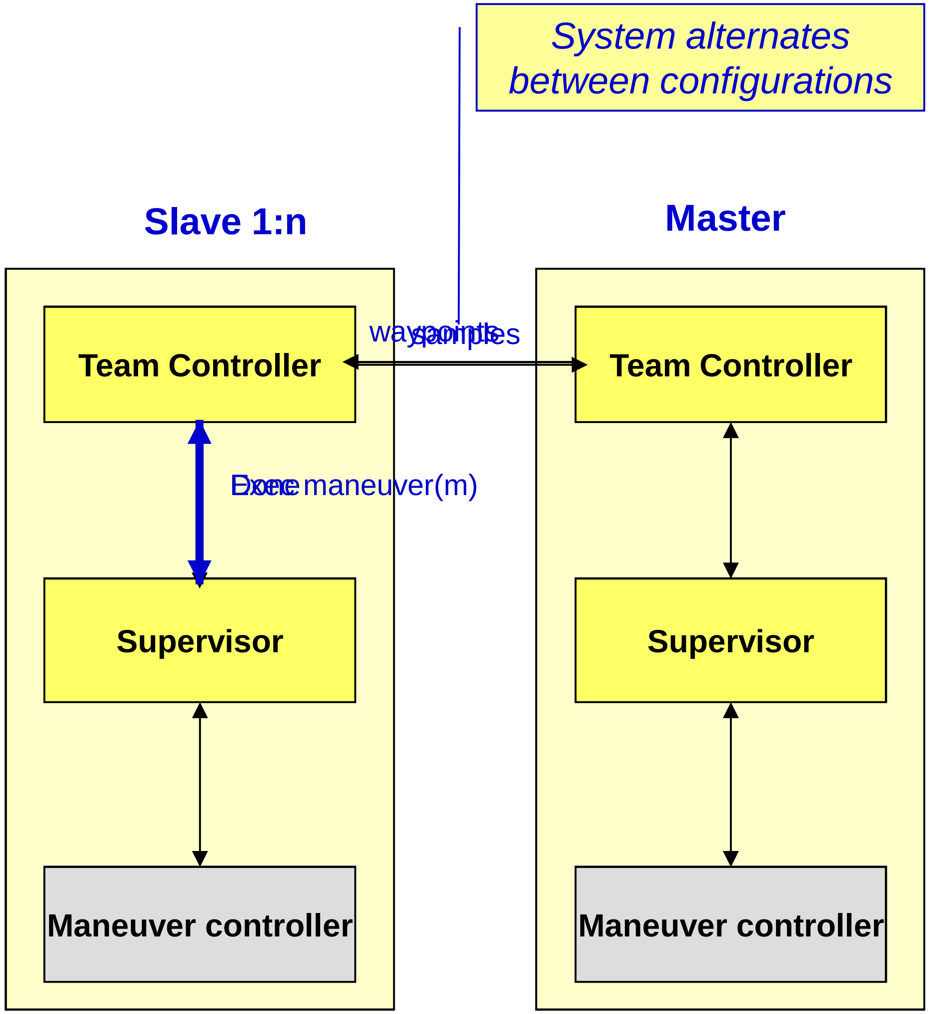
Specification S



- Find
  - control architecture = controllers + connections such that
    - Σ = V + control architecture satisfies the specification (simulation relation)

Control architecture

- Team controllers
  - One master; n slaves
  - Run the coordination algorithm
  - Handle structural adaptation and reconfiguration
- Vehicle supervisors
  - Interface with external controllers
  - Makes decisions on what maneuver to execute
- Maneuver controllers
  - Implement elemental feedback control maneuvers for each AUV
  - One active at a time
  - Goto(point)
  - Hold(point)



Formal model: dynamic network of hybrid automata

More formally...

- Formal model for team controllers
  - $T = T_M || T_{S1} || \ldots || T_{SN}$

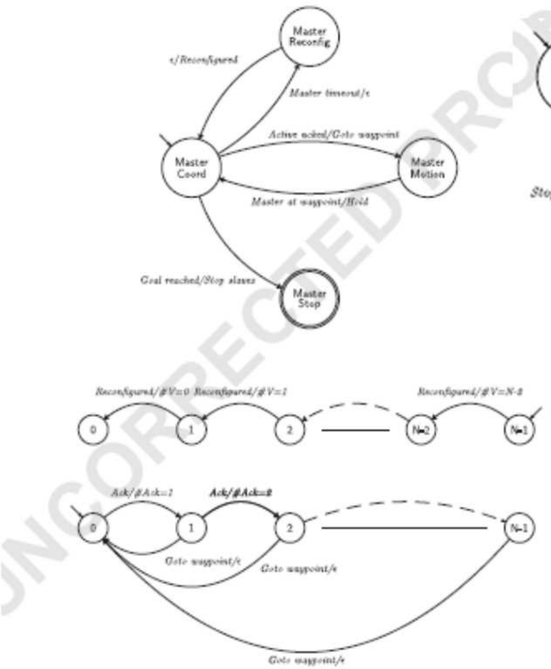


Figure 4. The master team controller is the parallel composition of three transition systems.

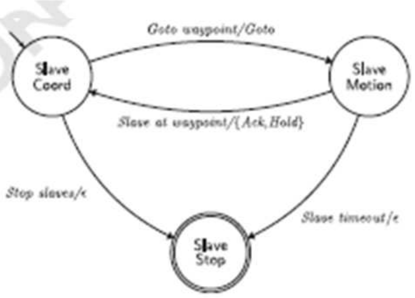


Figure 5. Slave team controller.

- Team controllers abstract the behavior of each vehicle
  - composition with supervisor and maneuver controller

- Assumptions
  - waypoint generation procedure produces feasible intervals for waypoints
  - maneuver controllers produce ensured results

- Theorem: T and S are bi-similar

New problems of optimal path coordination for multi-vehicle systems

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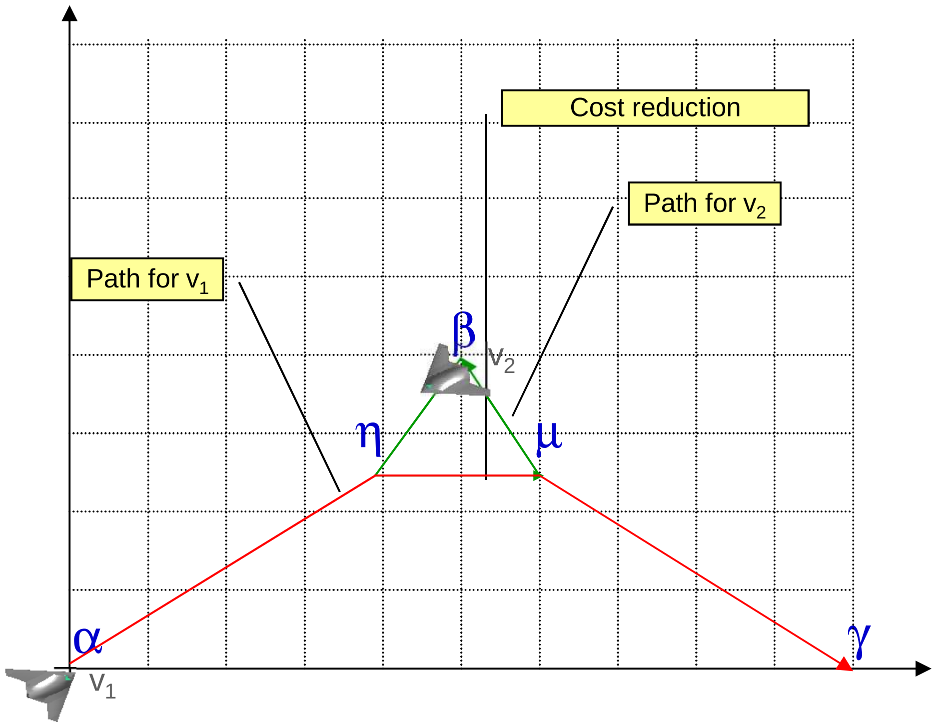
LSTS

Path coordination for 2 vehicles

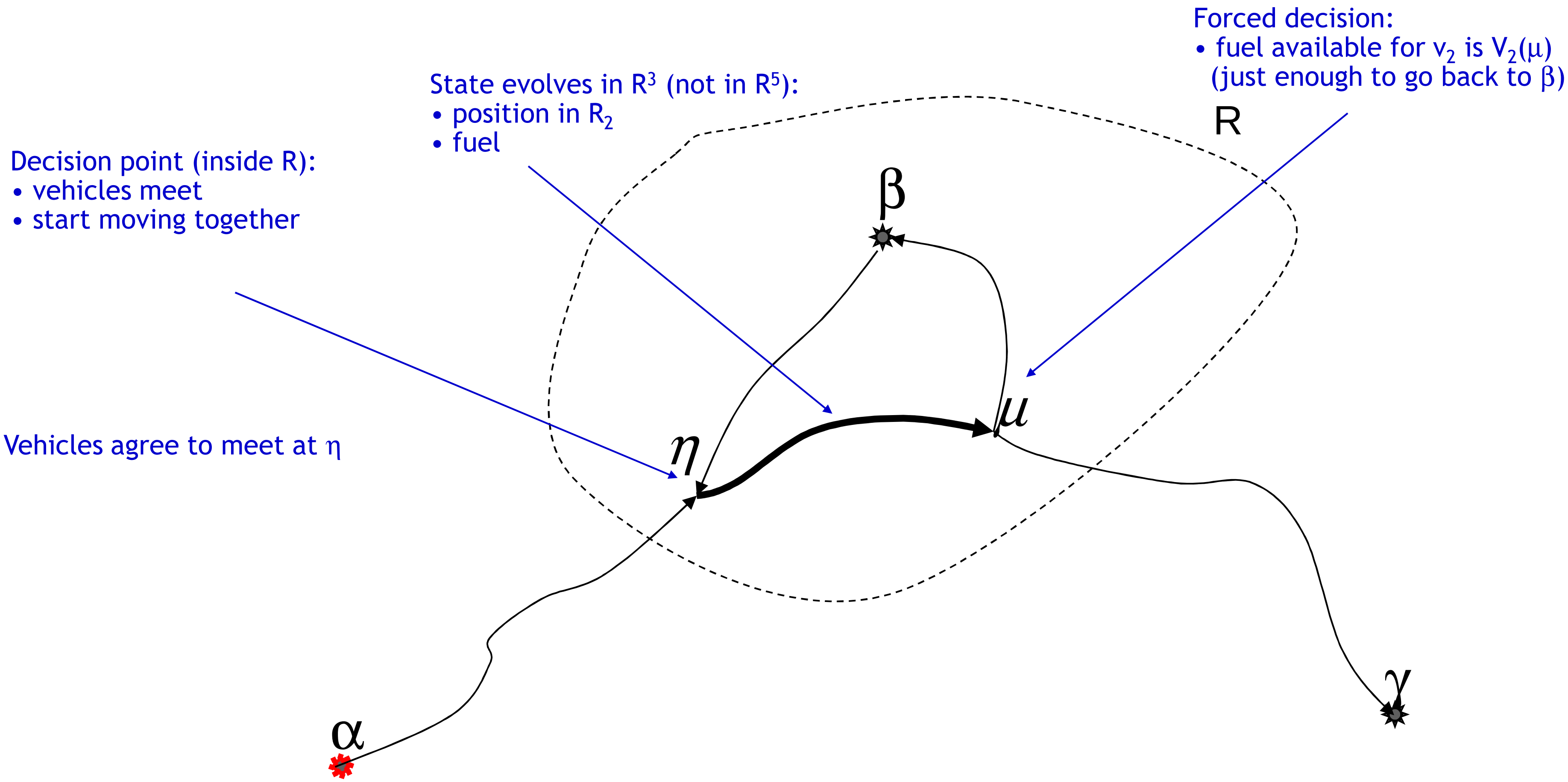
- Vehicle v_1
  - Find the optimal path from α to γ
  - Path cost is reduced when the position of v_1 *coincides* with the position of v_2
- Vehicle v_2
  - Departs from β and has to return to β
  - Has a limited amount of fuel Θ
- Operational constraints
  - If v_1 and v_2 meet at some point then separation occurs only when v_2 has to return to β (due to fuel constraints)



Related work

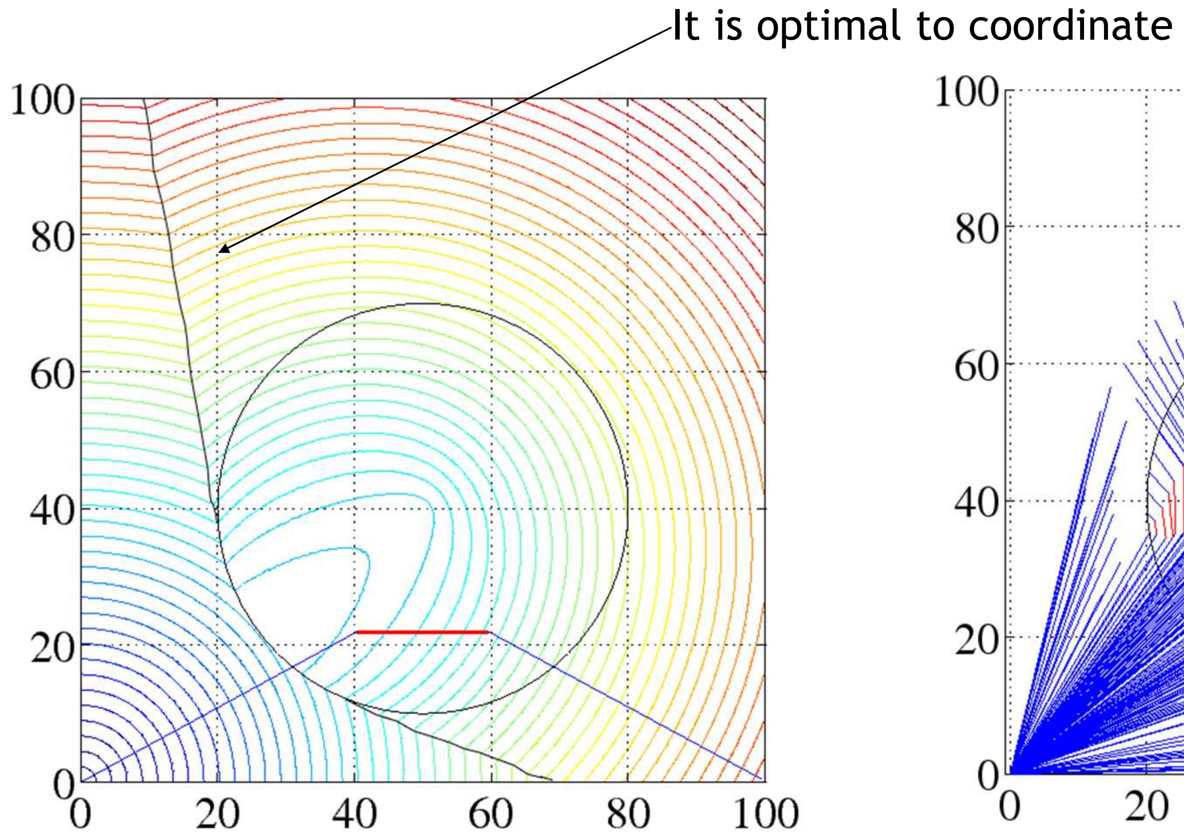
- Branicky (1999) extended the Fast Marching Method to optimal hybrid control problems:
  - Stair climbing problem: optimal to reach any position of a building with multiple floors. Each floor is connected to its neighboring floors by stairs. Floors correspond to discrete states, stairs correspond to transitions with fixed cost.
  - Very simple dynamics.
- Sethian[1] (2002) introduced motion coordination problems to illustrate the use of Ordered Upwind Methods for solving optimal hybrid control applications
  - Find an optimal trajectory for a person walking on a varied landscape and carrying a pair of inline roller skates (option to switch between walking and skating by paying a time penalty)
    - Modeled with two discrete states, thus requiring two copies of the same continuous-time state-space
    - Problem solved with the one value function defined on the hybrid state-space.

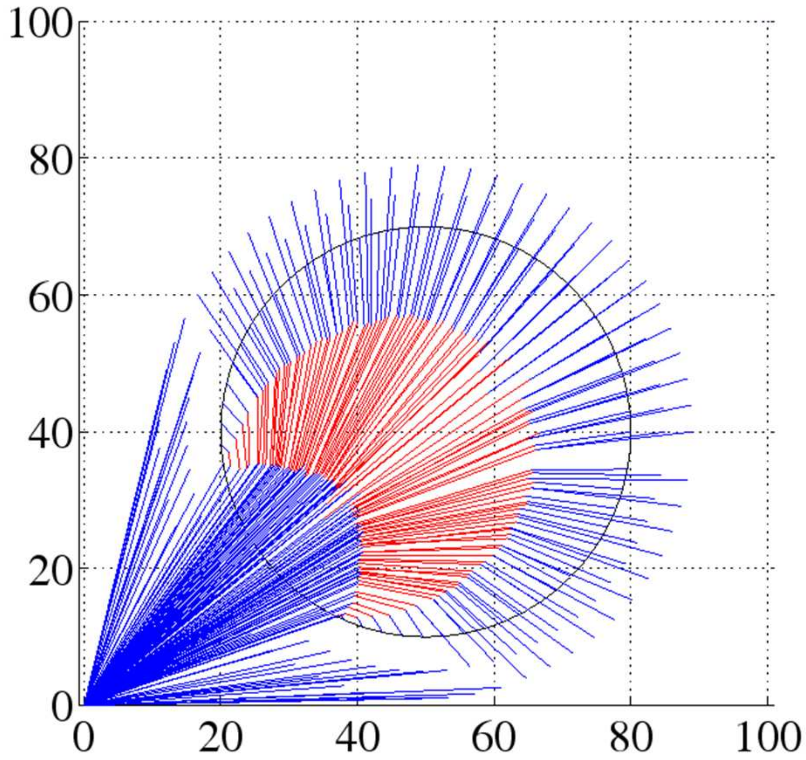
Structure of solution



- The integral constraint is converted to a state-constraint involving the value function V_2. This restricts the set of feasible controls so that we can apply dynamic programming.
  - P. Soravia, *Viscosity solutions and optimal control problems with integral constraints, Systems & Control Letters 40 (2000) 325-335*

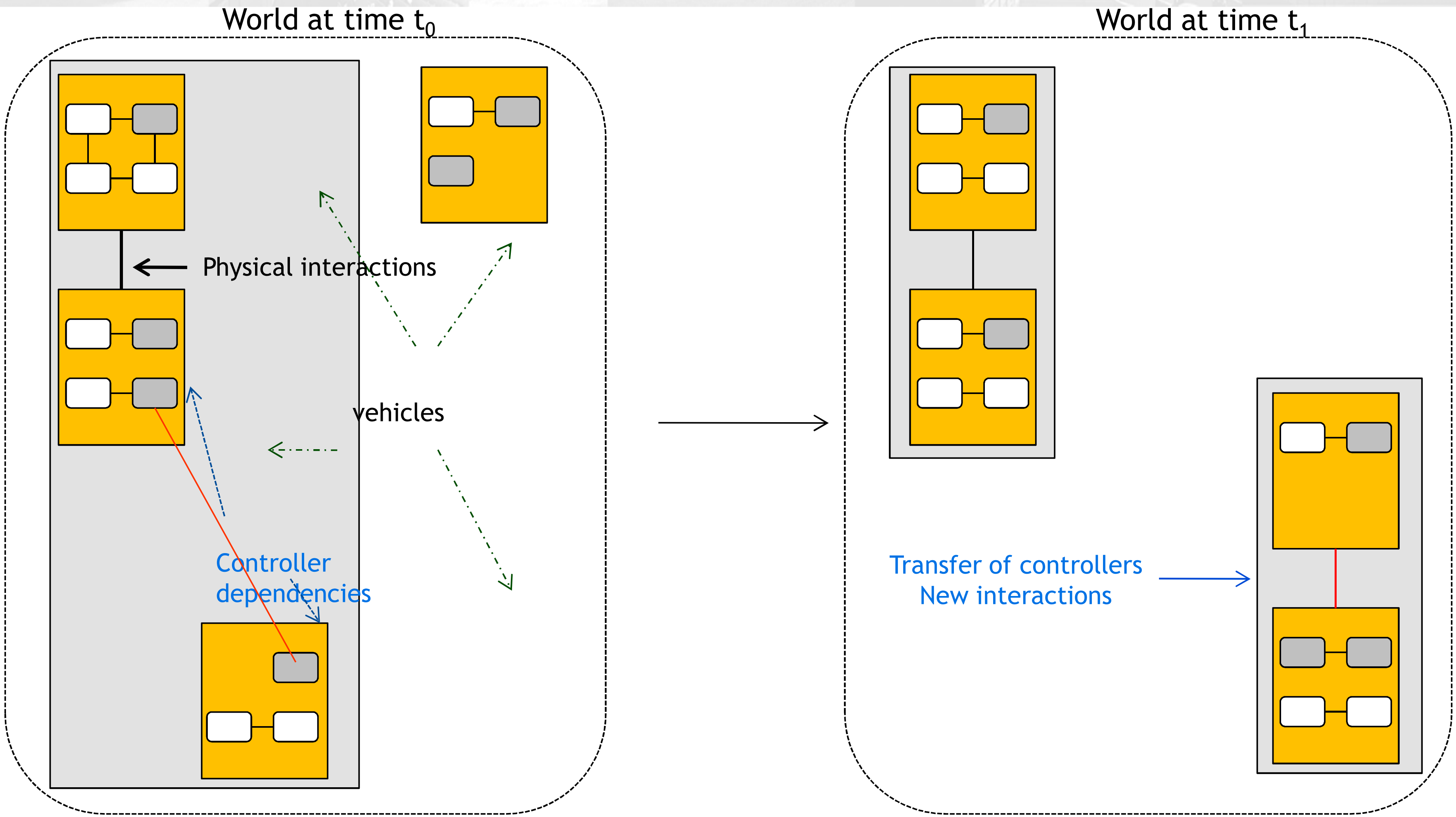
Value function approach





WHAT ARE WE MISSING?

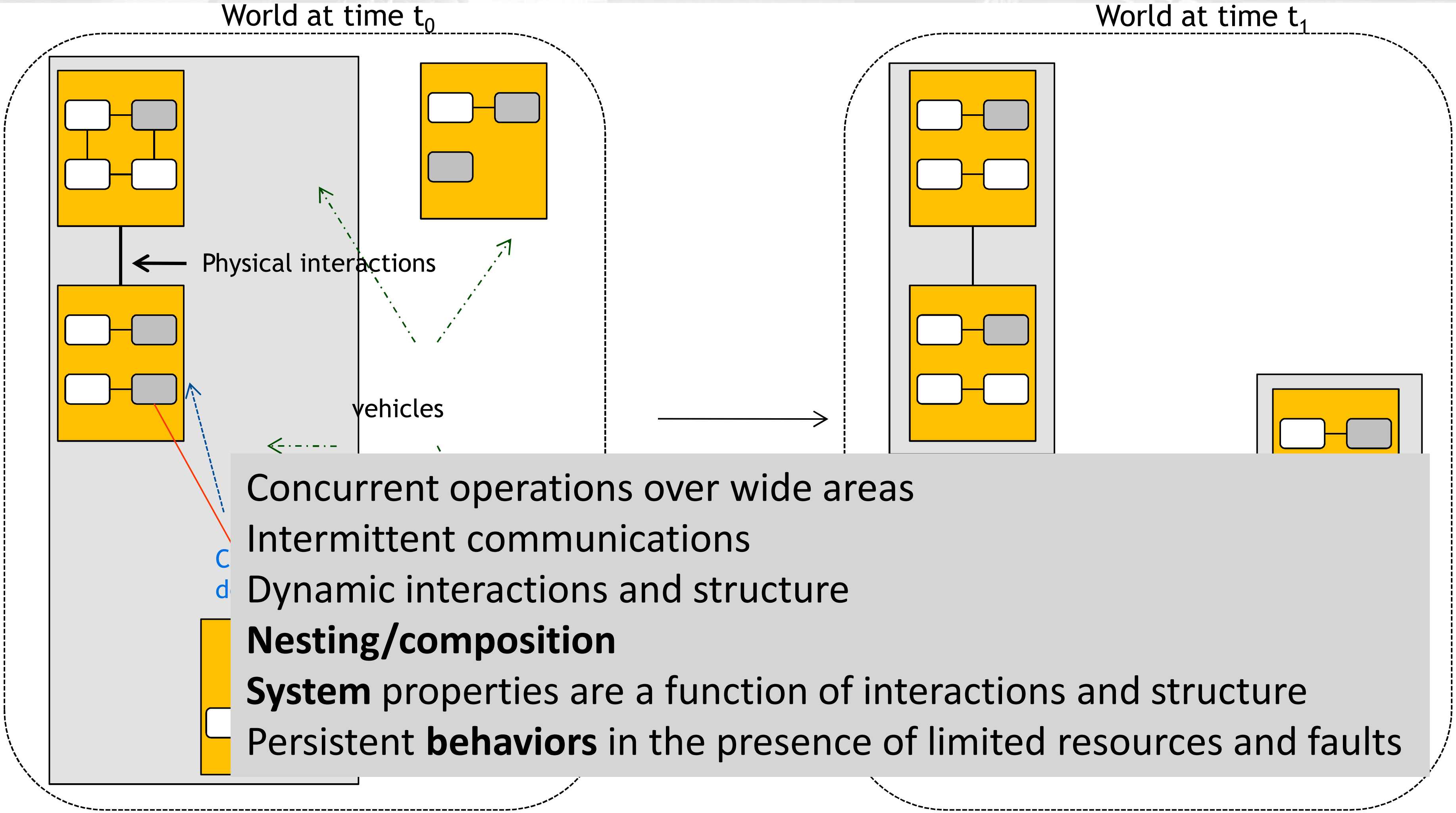
Simulink analogy…



Embed blocks in a 3 dimensional space; let blocks move according to laws of motion

World is **partially known** due to sensor and communication limitations; this leads to intermittent interactions

Simulink analogy…



Concurrent operations over wide areas
Intermittent communications
Dynamic interactions and structure
Nesting/composition
System properties are a function of interactions and structure
Persistent **behaviors** in the presence of limited resources and faults

Embed blocks in a 3 dimensional space; let blocks move according to laws of motion
World is **partially known** due to sensor and communication limitations; this leads to intermittent interactions

System's view

- What is the state(s) of the system?
- What are the dynamics?
- How do we specificy system's behavior?
- What new behaviors can be specified?

MODELLING CHALLENGES

Two types of entities

- Physical entities
  - Host computational entities (computational environment)
  - Provide sensing and comms capabilities to computational entities
  - Dynamics depend on physical interactions with other physical entities and the environment (laws of physics)
  - Actions may affect other physical entities and the environment
  - Composable
- Computational entities (e.g., controllers)
  - Reside on physical entities
  - Allowed to migrate through communication channels
  - Dynamics depend on interactions with other local or remote physical entities (laws of computation)
  - Composable

Set-valued state and coupled dynamics

- State of physical entities
  - Motion
  - List of physical resources
  - List of computational entities
  - List of available communication channels
  - List of physical interactions
- Controls
  - Motion
  - Manage local resources
  - Modify the environment
  - Compose
- State of computational entities
  - Location
  - List of computational interactions
  - Internal state
- Controls
  - Migrate
  - Enable/disable communication channels of physical entities (permissions)
  - Establish/delete interactions
  - Compose
  - Internal

Dynamic reconfiguration

"Dynamic reconfiguration is a common feature of communicating systems.

The notion of link, not as a fixed part of the system but as a datum that we can manipulate, is essential for understanding such systems.

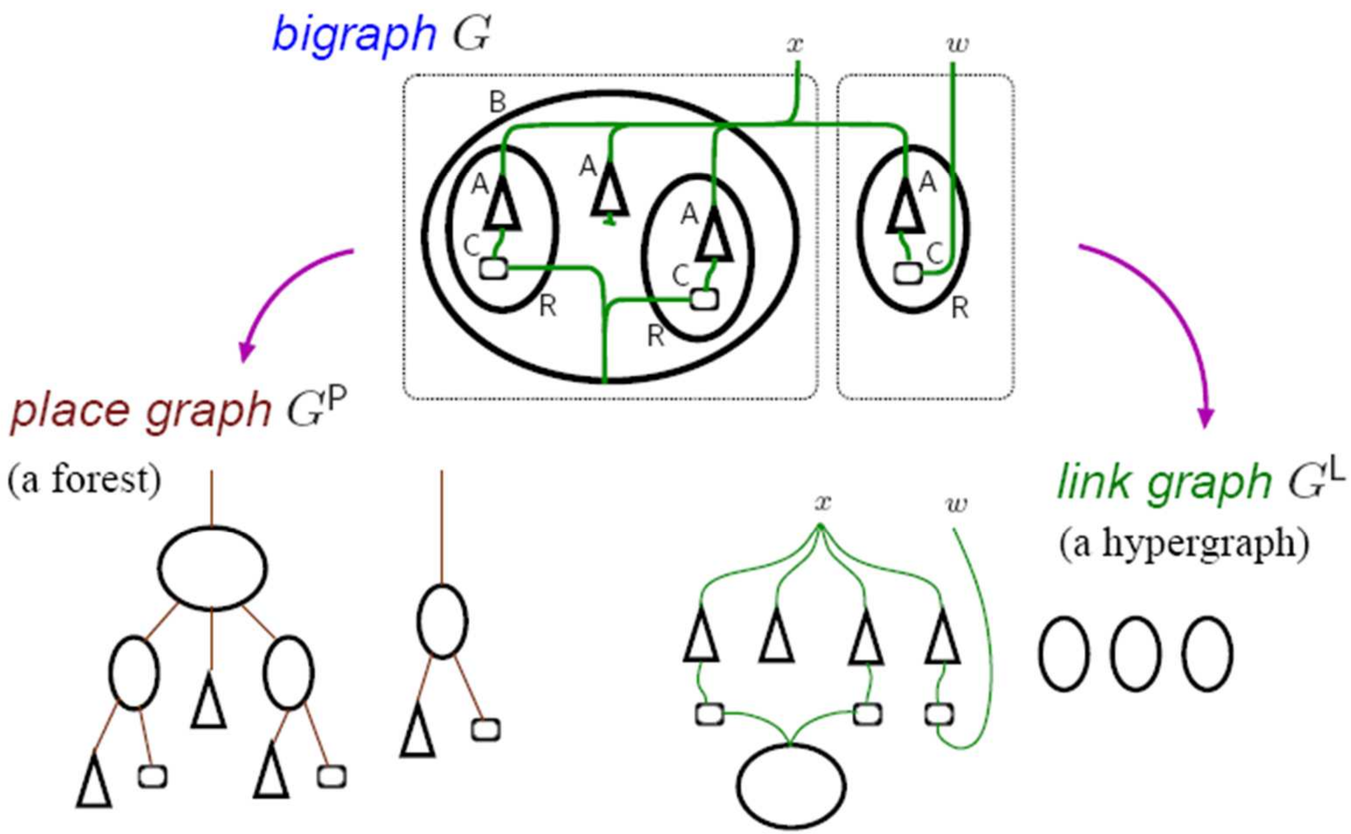
What is the mathematics of linkage?

The theories of computation are evolving from notions like value, evaluation and function to those of link, interaction and process."

Milner, 1999

Bigraphs (Milner 2008)

The ‘bi-’ structure of a bigraph



Bigraphical reaction rules
Lacks dynamic systems’ view

CONTROL (?) CHALLENGES

Specifications

- "Traditional" specifications for an augmented state-space
  - Invariance
  - Attainability
  - Optimality
- Examples
  - A computational entity should remain in a given region independently of the physical entity where it resides.
  - At least of vehicle of a given type remains in a given region.
  - A structure of vehicles and controllers remains in a given region to provide a region-wide service.
  - A structure of vehicles and controllers should attain a given state.

Why is it difficult?

- Lack of global controllers
- Partial information setting
- Complex state-spaces and controls
- Permissions for communicating and interacting
- Spatial rendezvous for coordination
- Computational entities can be created/deleted on the fly
- Network effects
- Dynamic programming principle may not apply

Controlling to compute and computing to control


Conclusions
Work at the intersection of computation and control
Developments should be evaluated and tested in real systems
Inspiration comes from networked vehicles but applicable to other domains
Provides food for thought???