Multi-vehicle systems for ocean observation: are we missing something?

João Tasso de Figueiredo Borges de Sousa

João Sousa

Laboratório de Sistemas e Tecnologias Subaquáticas
Faculdade de Engenharia da Universidade do Porto
Portugal
jtasso@fe.up.pt

Universidade do Porto
FEUP Faculdade de Engenharia

Outline

- Laboratory overview
- Vehicle systems
- Approach
- Operations
- Conclusions

LABORATORY OVERVIEW

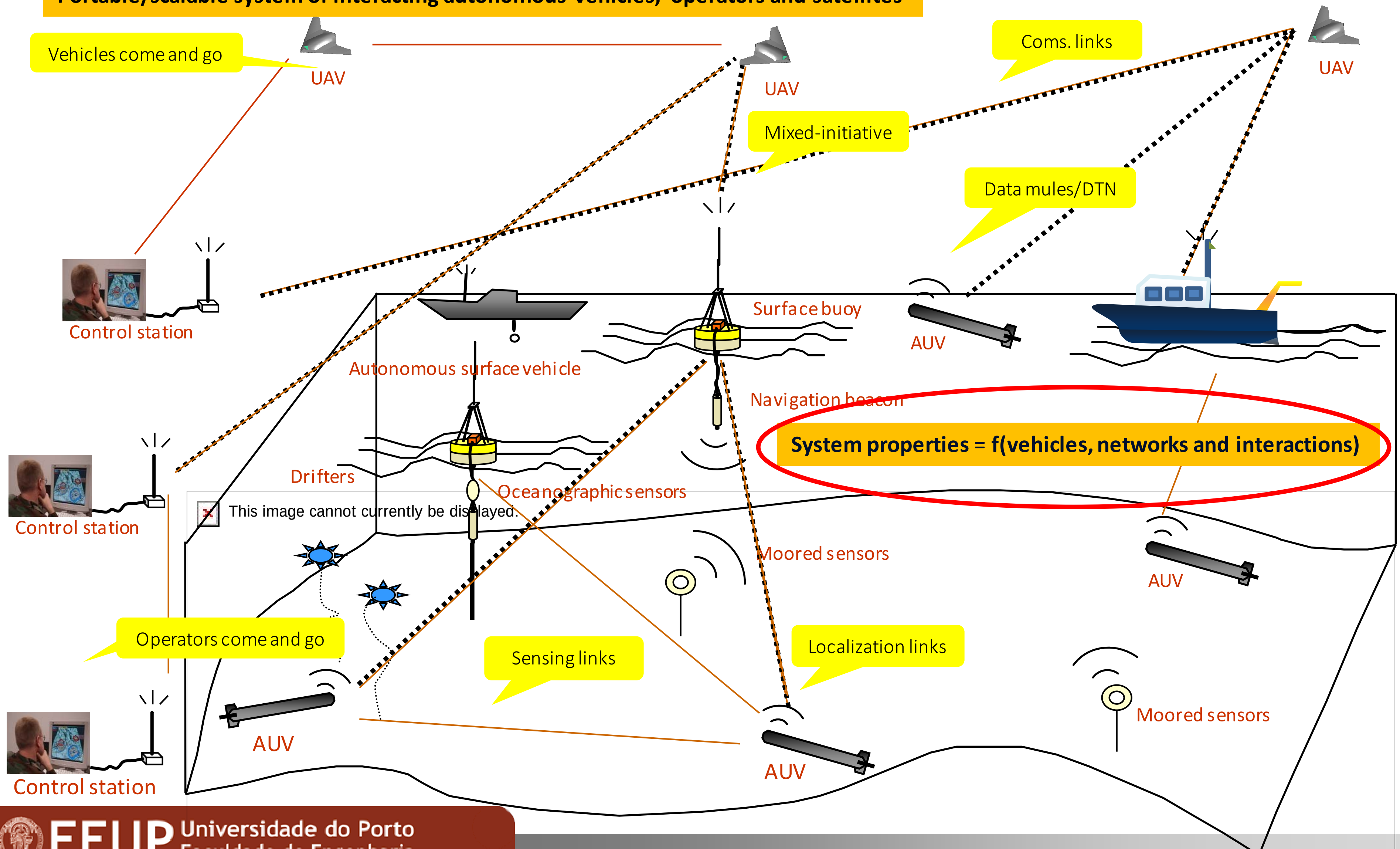
U.PORTO

FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO 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
ANTEX X03 UAV
Execution
Cooperatio n
Data
Plan
Operation in GPS-restricted environments
ANTEX X02 UAV
Sense & avoid
ANTEX X01 UAV
Interoperability with third-party systems
Geographic features tracking
Advanced training
ASV
Acoustic Position Tracking
ISURUS
Plume Tracking
SeaCon
Mine Hunting
ROV-IES
Inspection
NAUV
Mapping
Acoustic Comunications
http://www.fe.up.pt/lsts
NOPTILUS
C4C
SeaCon System
PITVANT
U.PORTO
FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO
LSTS
União Europeia FEDER
Governo da República Portuguesa
COMPETE
PITVANT
PITVANT
PITVANT
PITVANT

Vision

Portable/scalable system of interacting autonomous vehicles, operators and satellites



More than motion coordination ☺

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.”

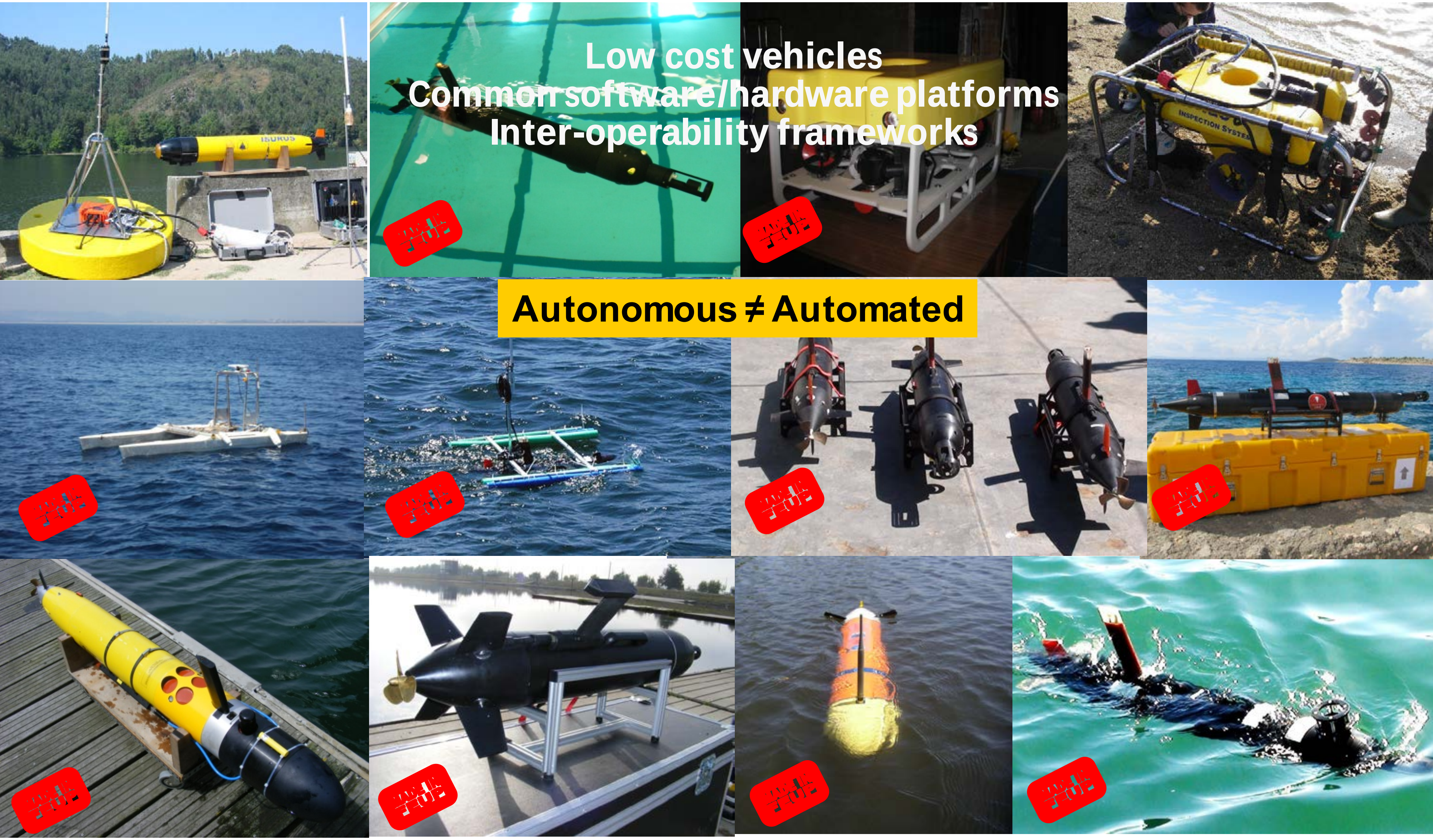
Milner, 1999

Cooperation

- Portugal
  - Portuguese Navy and Air Force
  - Porto harbor
  - IPMA
  - Instituto Superior Técnico
  - DGPM
  - Task group for the extension of the continental shelve
  - Oceanscan MST (spin-off)
- USA
  - US Coast Guard
  - MBARI
  - UC Berkeley
  - Naval Postgraduate School
  - NASA Ames
  - University of Michigan
  - Naval Undersea Warfare Center
- Europe
  - AMOS - NTNU (NO)
  - Royal Institute of Technology (SE)
  - Supelec (FR)
  - Naval Undersea Research Center (NATO)
  - National Oceanography Center (UK)
  - Imperial College (UK)
  - Plocan (SP)
  - Delft University (NL)
  - EU/NATO/EDA project partners
    - NOPTILUS - FP7
    - SUNRISE - FP7
    - NECSAVE - EDA
    - NETMAR - Interreg
    - SAFEPORT - NATO
    - PITVANT - PO MOD
    - UReady4OS - DG-ECHO
    - BRIDGES – H2020
    - ITN – Marine UAS – Marie Curie
- India
- Brasil

VEHICLE SYSTEMS

Ocean vehicles

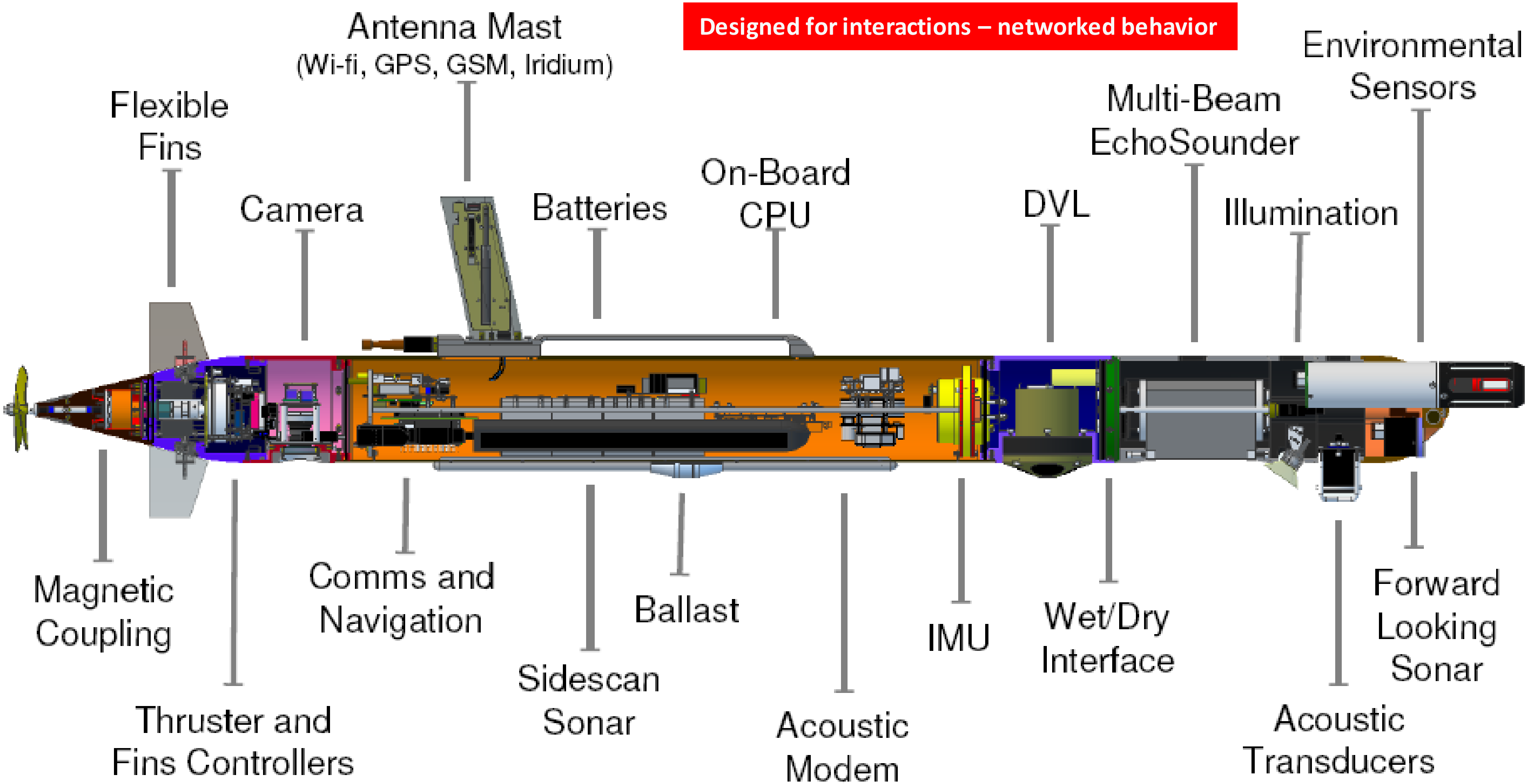


Low cost vehicles
Common software/hardware platforms
Inter-operability frameworks

Autonomous ≠ Automated

Light AUV (LAUV)

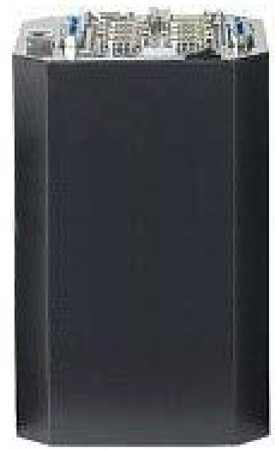
Designed for interactions – networked behavior



CONCURSO NACIONAL DE INOVAÇÃO BES
BANCO ESPÍRITO SANTO Fundação Ilídio Pinho / Siemens

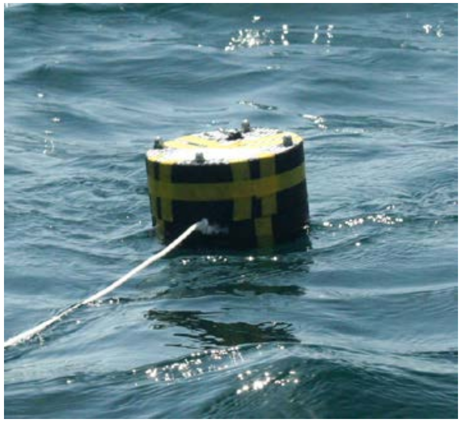
Coms gateways, *data loggers, drifters, fish tags*

Communications gateway



High performance data logger

Light data logger

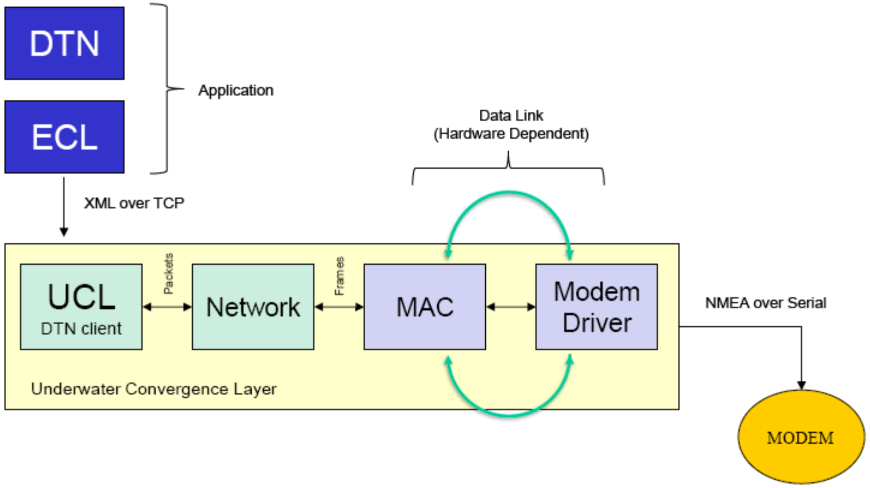


Drifter

Common hardware and software platforms

Drifters

Fish tags



Aerial vehicles

- PITVANT project – cooperation with POAF (MOD 2009-15)
  - Unmanned vehicle systems
    - 3 ANTEX01 (6.5 m wingspan)
    - 3 ANTEX02E (3.6m wingspan)
    - 8 ANTEX02 (2.4m wingspan)
    - 2 small wingspans
  - Stats
    - > 1400 autonomous flights
    - Day / night operations
  - Priority: flights over the ocean
    - Surveillance (fishing, polution, etc)
    - Long duration (> 8hours)

Common hardware and software platforms

UAS

UAV system

Flight time: 1h
Range: 10Km (video feed)
Hand launched or catapult launch
Fully autonomous (soon: no pilot required)

X8 based UAV (1.400 €)

- RC model based platform
- Autopilot
- Onboard computer for autonomy
- WiFi coms (up to 10Km range)
- IP video camera
- HD digital camera or IR camera
- DUNE on-board software
- IMC command and control protocol
- Battery powered

Ground station

- Laptop & antennas
- Neptus command and control software
- IMC command and control protocol
- Multi-vehicle control
- Internet enabled

Data vizualization/storage

Applications

Maritime surveillance
Aerial photography/mapping
Biological studies
Search and rescue
Fisheries
Incident response (floods)
Inspection of power lines
Ilegal hunting

I. Prodan. S. Olaru. R. Bencatel, J. Borges de Sousa, Cristina Stoica, and Silviu-Iulian Niculescu, "**Receding horizon flight control for trajectory tracking of autonomous aerial vehicles**", Control Engineering Practice journal, Elsevier, 2013.

APPROACH

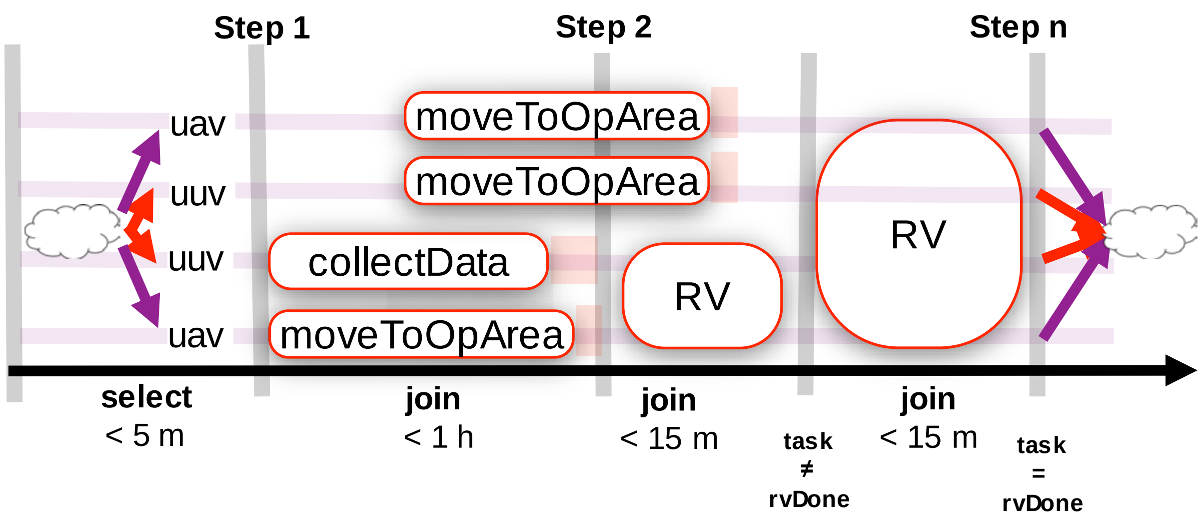
Abstract model

Extensible and verifiable control architecture

Uniform software framework with support for interoperability

Abstract model

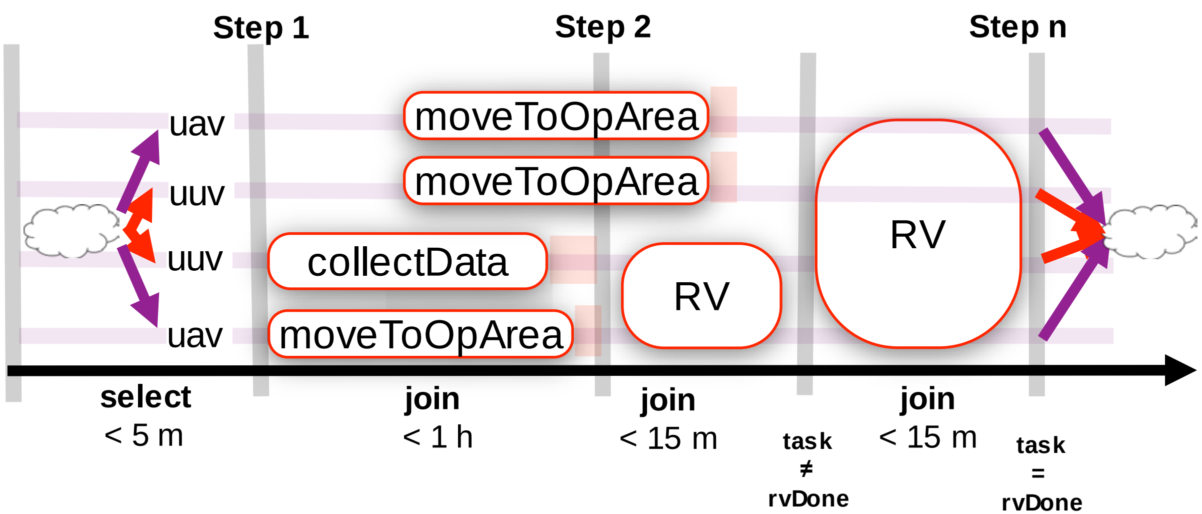
- System has a pool of vehicles/assets
- System evolves through several steps
- Vehicle/assets execute tasks in each step (vehicle timeline)
- Communications take place at the end of each step for coordination



J. Borges de Sousa, K. H. Johansson, J. Estrela da Silva, and A. Speranzon, "**A verified hierarchical control architecture for coordinated multi-vehicle operations**", International Journal of Adaptive Control and Signal Processing,, Volume 21, Issue 2-3, Pages 159 – 188, 2005.

Control architecture

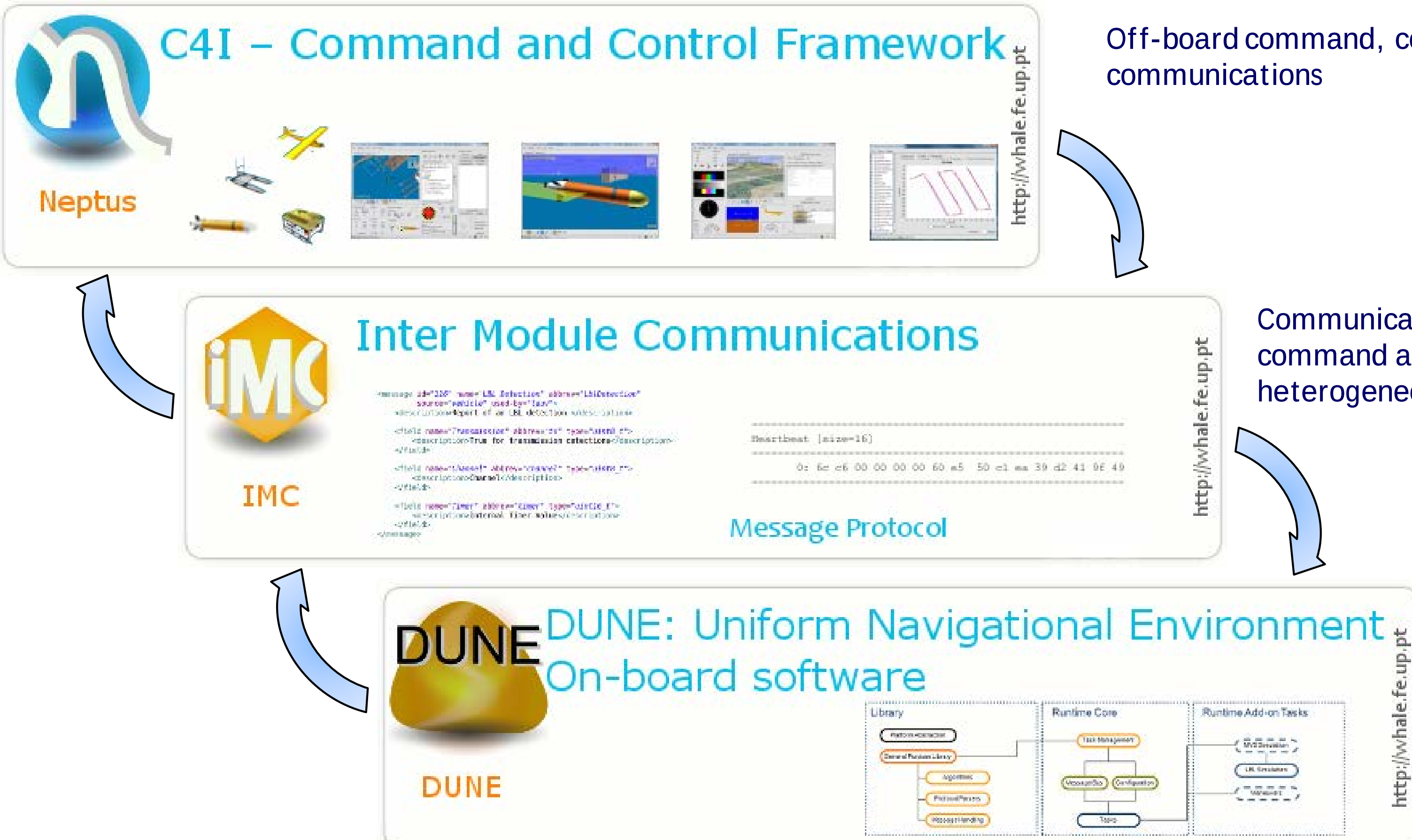
- Vehicles deliver computation, communications, power, motion, and sensing primitives
- System level specifications are given on a step transition system
- Each step describes what each vehicle (or ensembles) should be doing



- Motion primitives with guaranteed results or predictable failure model (reach sets)
- Planning for iterated rendezvous (for liveness)
- Layered control architecture
  - Lower layers: low level vehicle control, maneuvers, sensor configuration, communication configuration
  - Higher layers: multi-vehicle controllers that may come and go; time varying control links

Software tool chain

Field tested every other week with ocean and air vehicles



Off-board command, control and communications

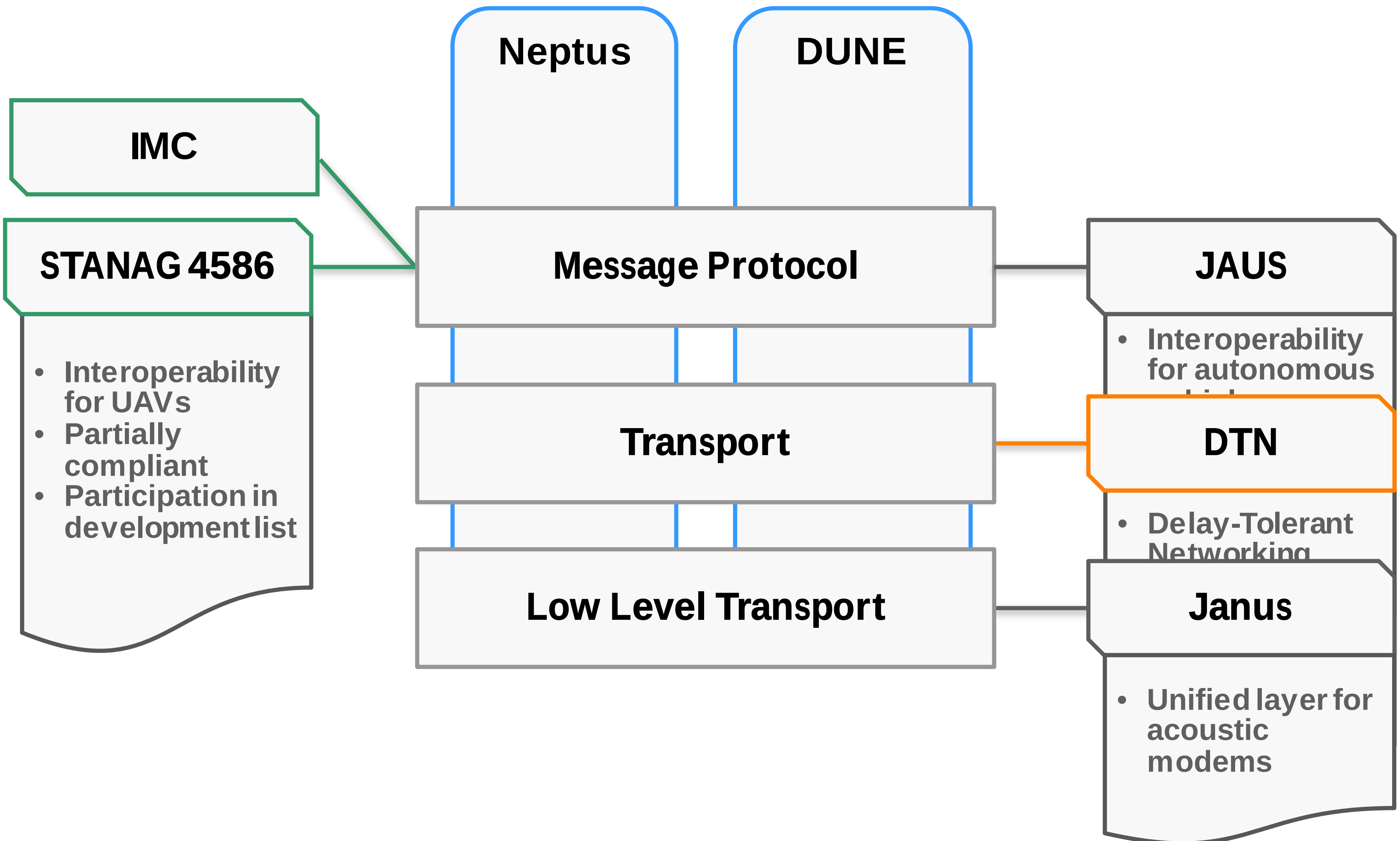
Communication protocols for command and control of heterogeneous systems

Onboard software (vehicles, buoys, data loggers)

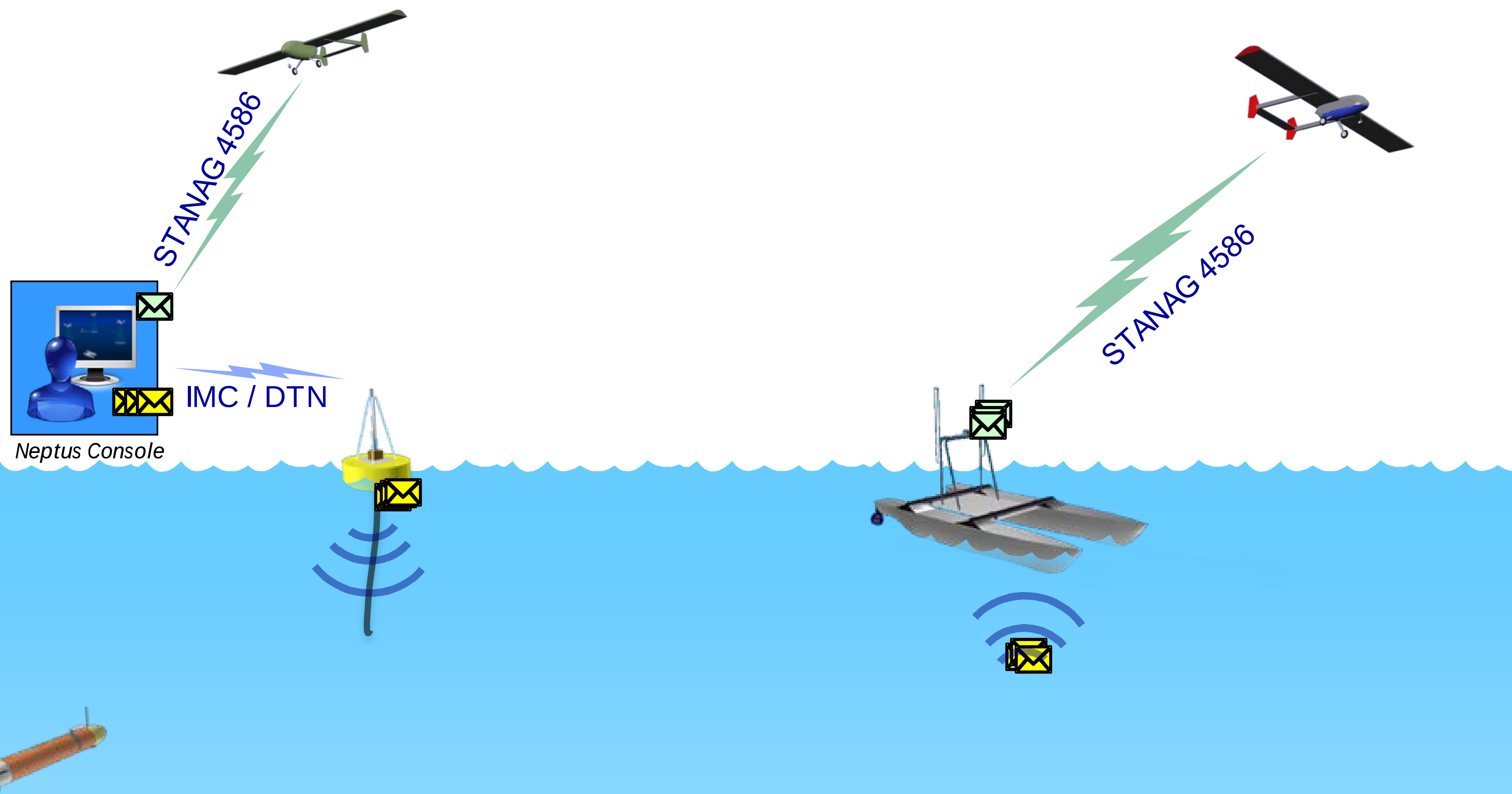
J. Pinto, P. Sousa Dias, R. Martins, J. Fortuna, E. R. B. Marques, and J. Borges de Sousa, "**The LSTS tool chain for networked vehicle systems**", Proceedings of the IEEE/MTS OCEANS'13, Bergen, June, 2013.

User group: PT, US, NL, NOR, SWE, SP, FR, UK, DE, GR, IN, QT

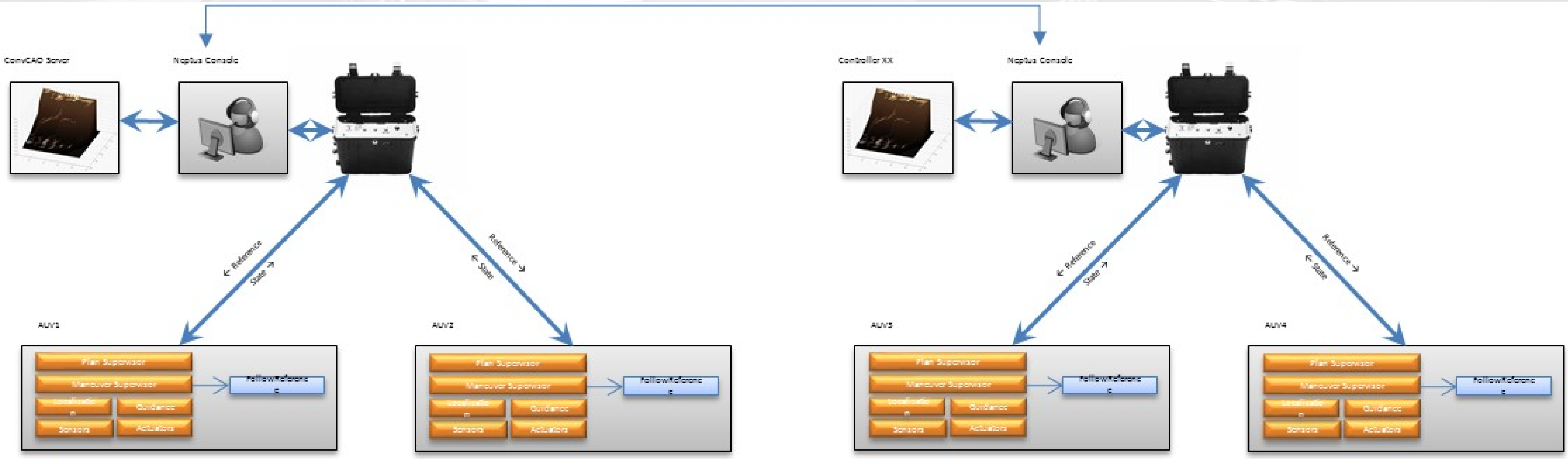
Layered communications architecture

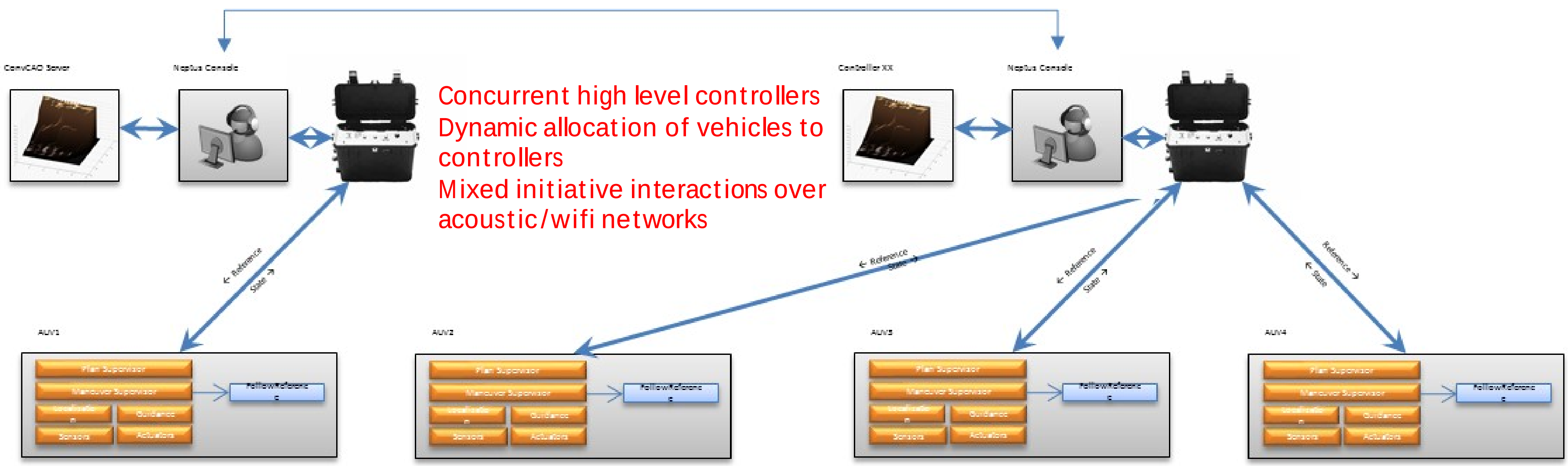


Operations under intermittent connectivity



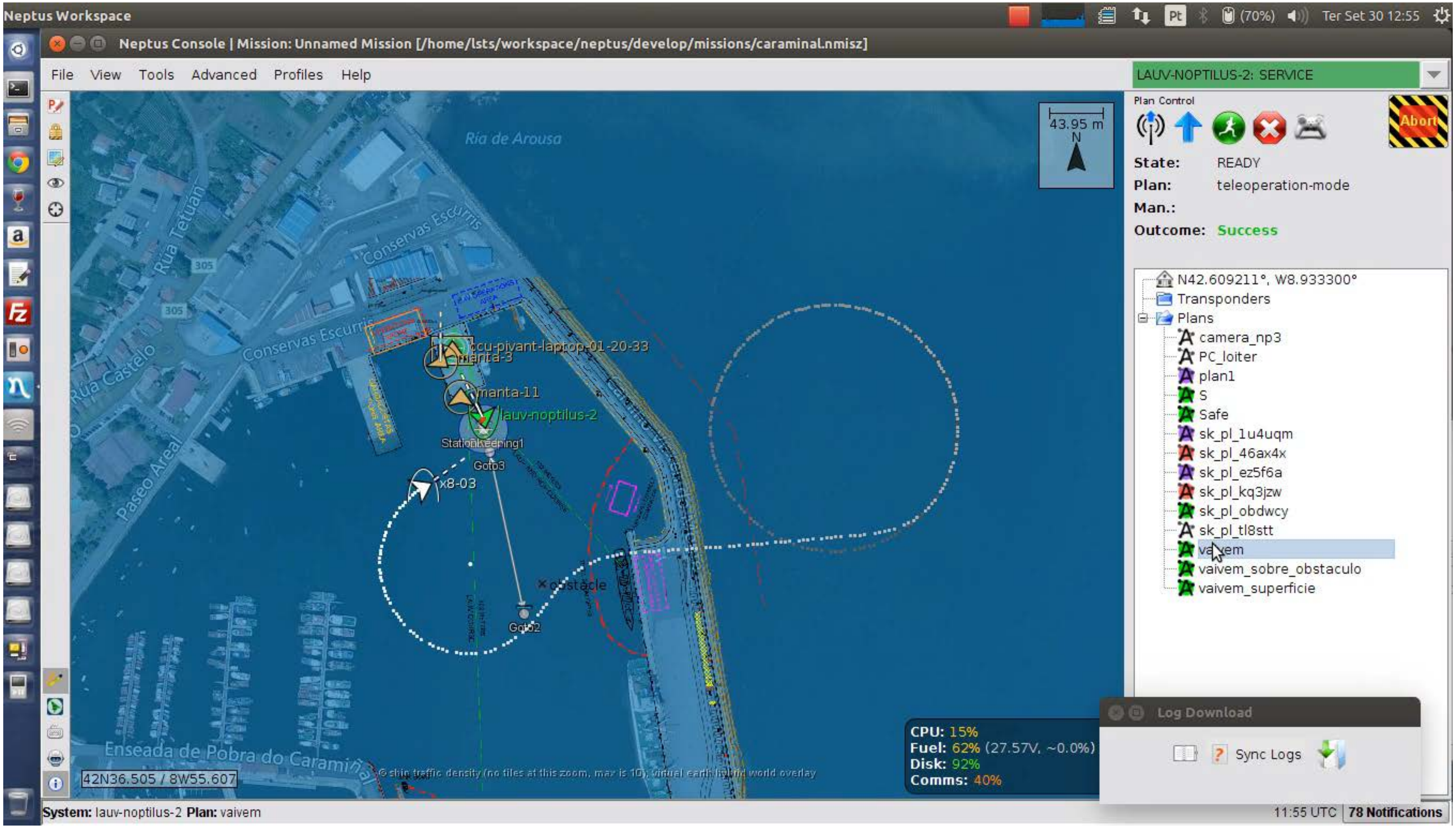
Multi-vehicle systems





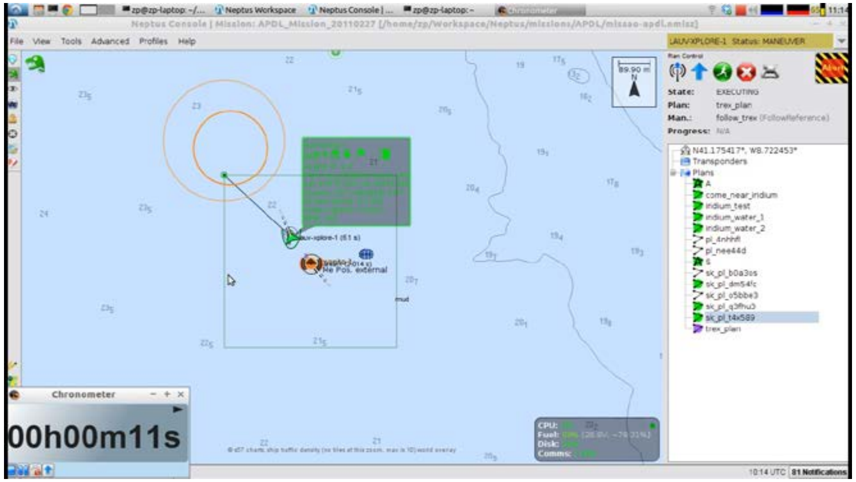
Concurrent high level controllers
Dynamic allocation of vehicles to controllers
Mixed initiative interactions over acoustic/wifi networks

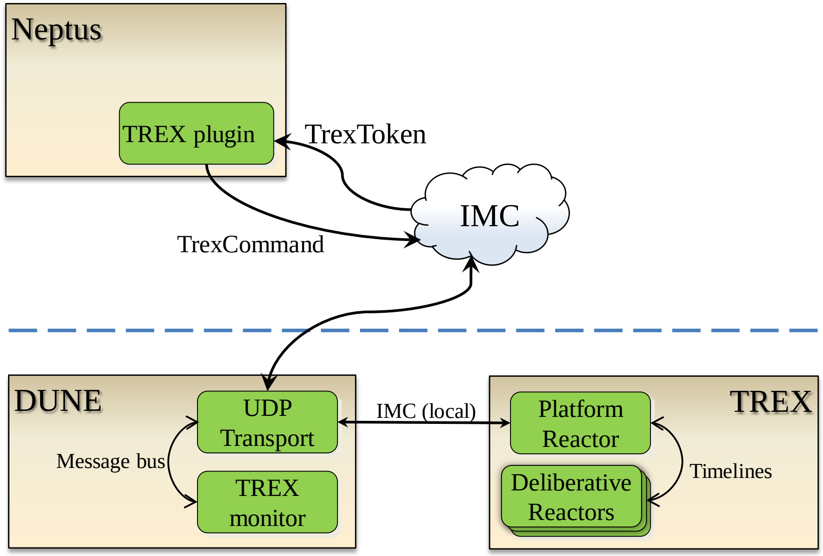
Multi-vehicle command and control



Onboard deliberation (T-REX / Europa)

- T-REX interacts with onboard DUNE
- Plans generated onboard (TREX runs on secondary CPU)
  - When new objectives are received (plan adaptation)
  - When there is an error executing some objective (replanning)

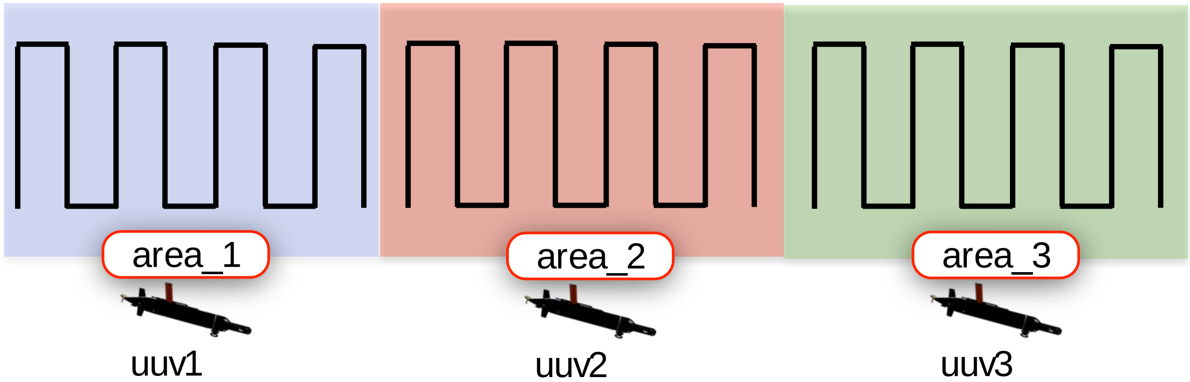


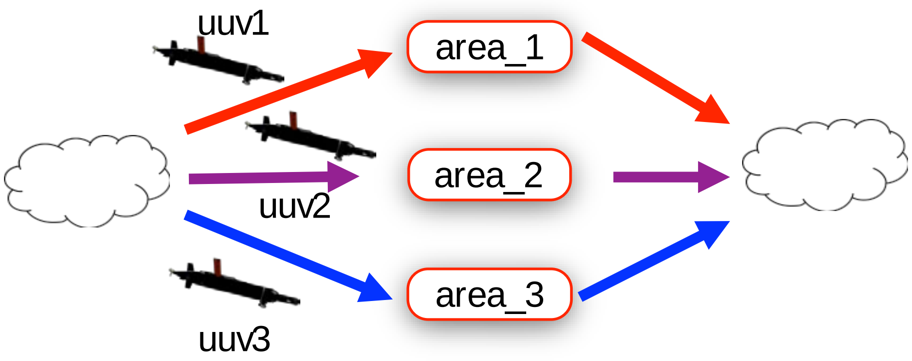


M. Faria, J. Pinto, F. Py, J. Fortuna, H. Dias, R. Martins, F. Leira, T. Arne Johansen, J. Borges de Sousa, and K. Rajan, "**Coordinating UAVs and AUVs for oceanographic field experiments: challenges and lessons learned**", Proceedings of the 2014 IEEE International Conference on Robotics and Automation (ICRA), Hong-Kong, May 31 – June 7, 2014.

Network vehicles language (NVL)

- Tasks and resources





Eduardo R.B. Marques, Manuel Ribeiro, José Pinto, João Borges de Sousa and Francisco Martins, "**NVL: a coordination language for unmanned vehicle networks**", Intelligent Robotics and Multi-Agent Systems (IRMAS), Coimbra, April 2015.

NVL code

- Coordinate parallel execution of tasks

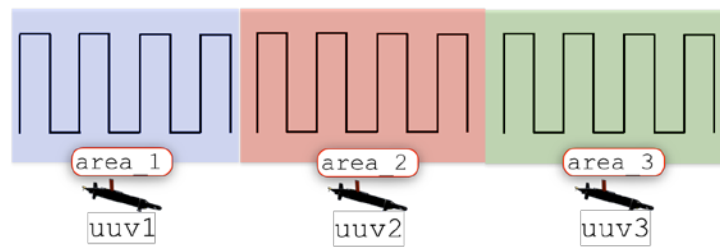
Task controllers

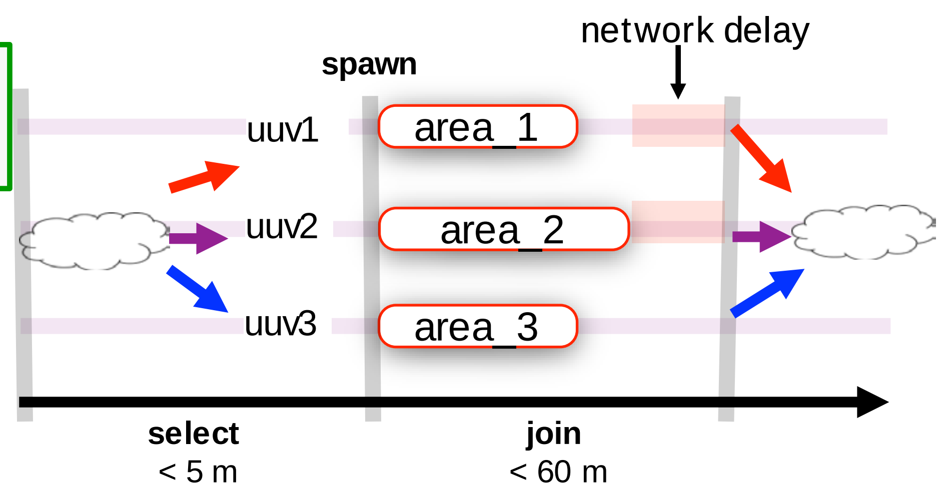
Selection of vehicles

Launch tasks

Wait for task completion

```
controller area_1 { ...
controller area_2 { ...
controller area_3 { ...
procedure main {
  select 5m
    uuv1 (type: "UUV")
    uuv2 (type: "UUV")
    uuv3 (type: "UUV")
  then {
    spawn task1 area_1(uuv:uuv1)
    spawn task2 area_2(uuv:uuv2)
    spawn task3 area_3(uuv:uuv3)
    join 60m task1 task2 task3
  }
}
```





Dynamic binding of controllers

Future: transfer controllers

Steps

NVL code

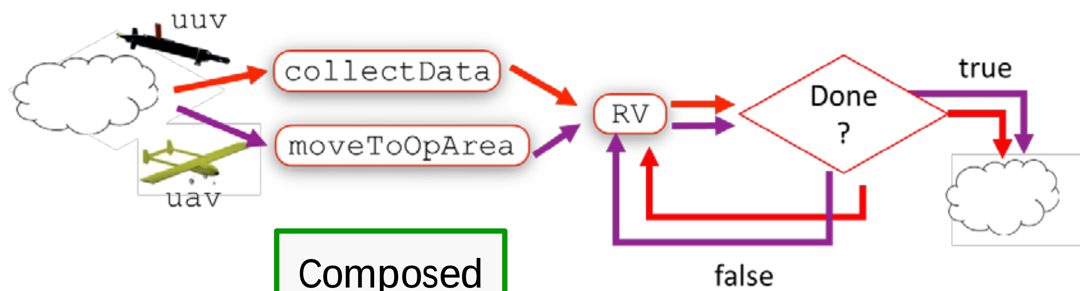
- Rendezvous

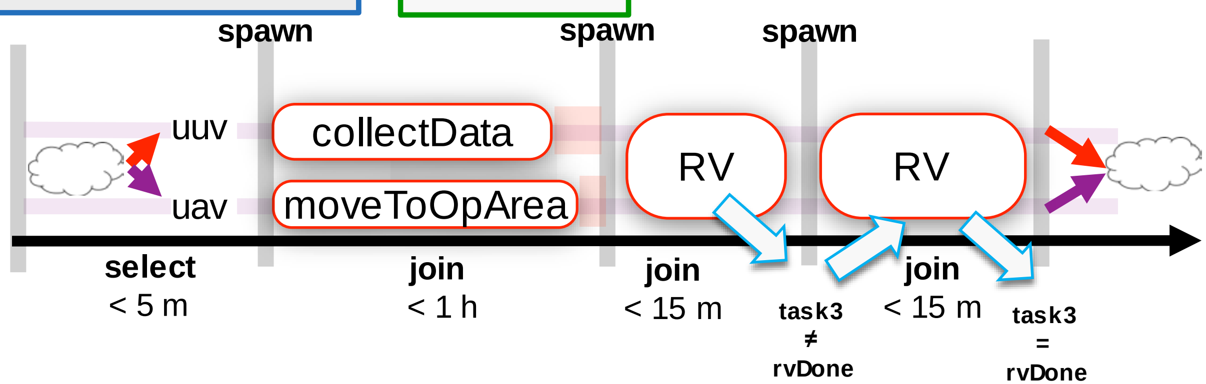
```
...
procedure main {
  select 5m
    uuv ( type: "UUV")
    uav ( type: "UAV")
  then {
    spawn task1 collectData (survey: uuv)
    spawn task2 moveToOpArea (mule: uav)
    join 1h task1 task2
    repeat {
      spawn task3 RV(survey: uuv, mule: uav)
      join 15m task3
    } until task3 = rvDone
  }
  or {
    delay 1h
    continue main
  }
}
```

Composed task

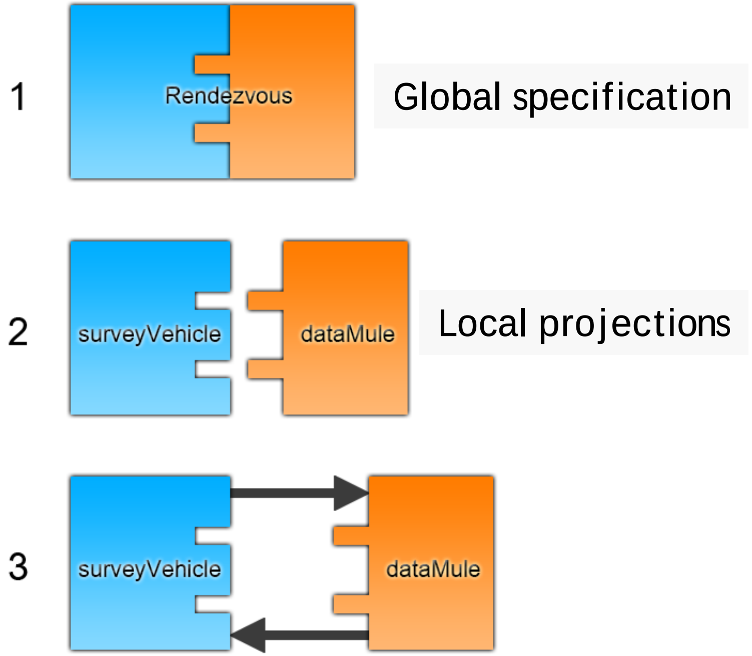
Cycle

Error handling

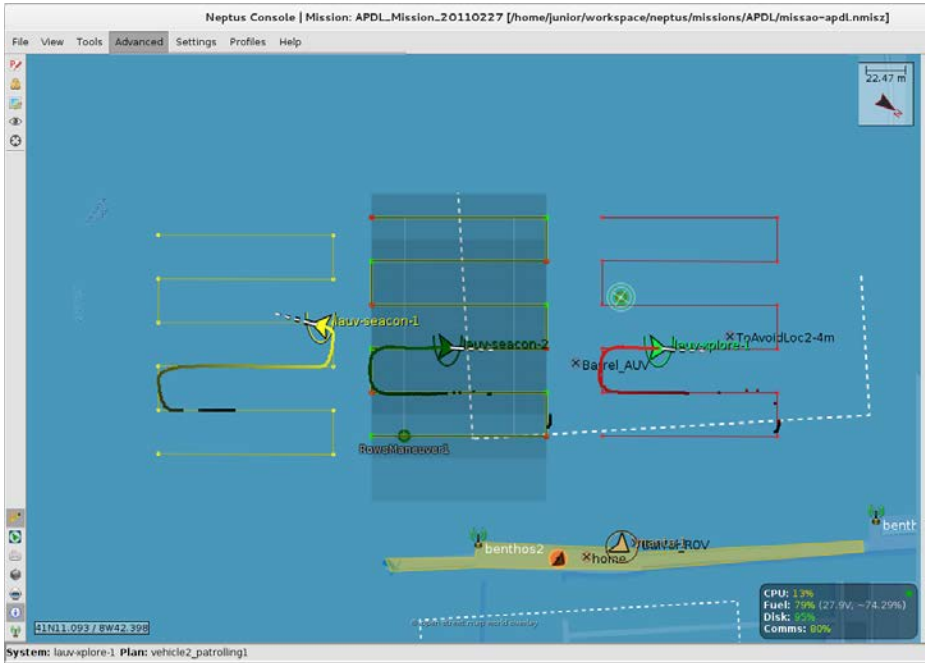


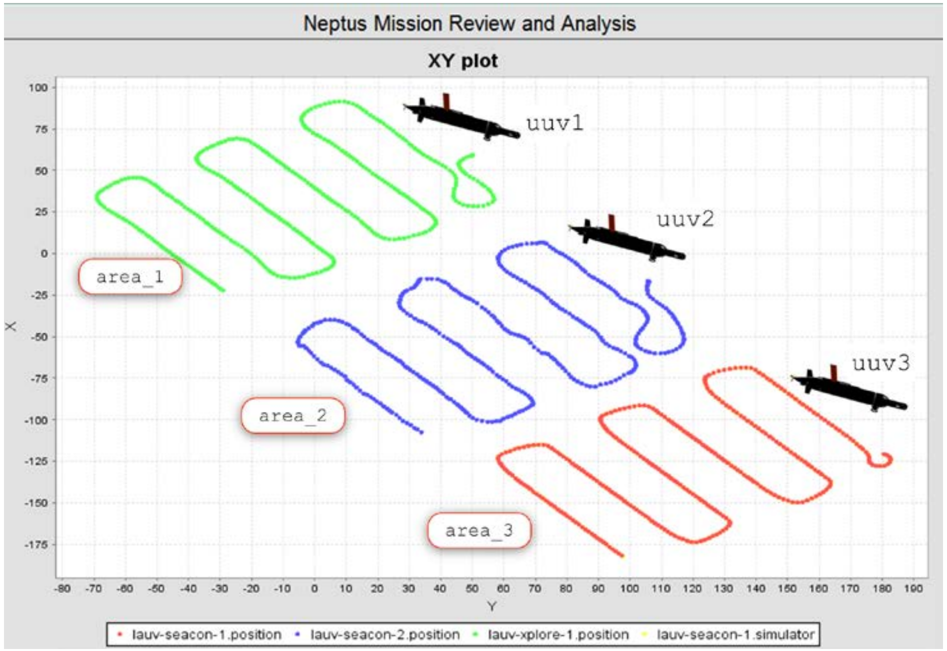


Global specifications and projections



NVL field trials

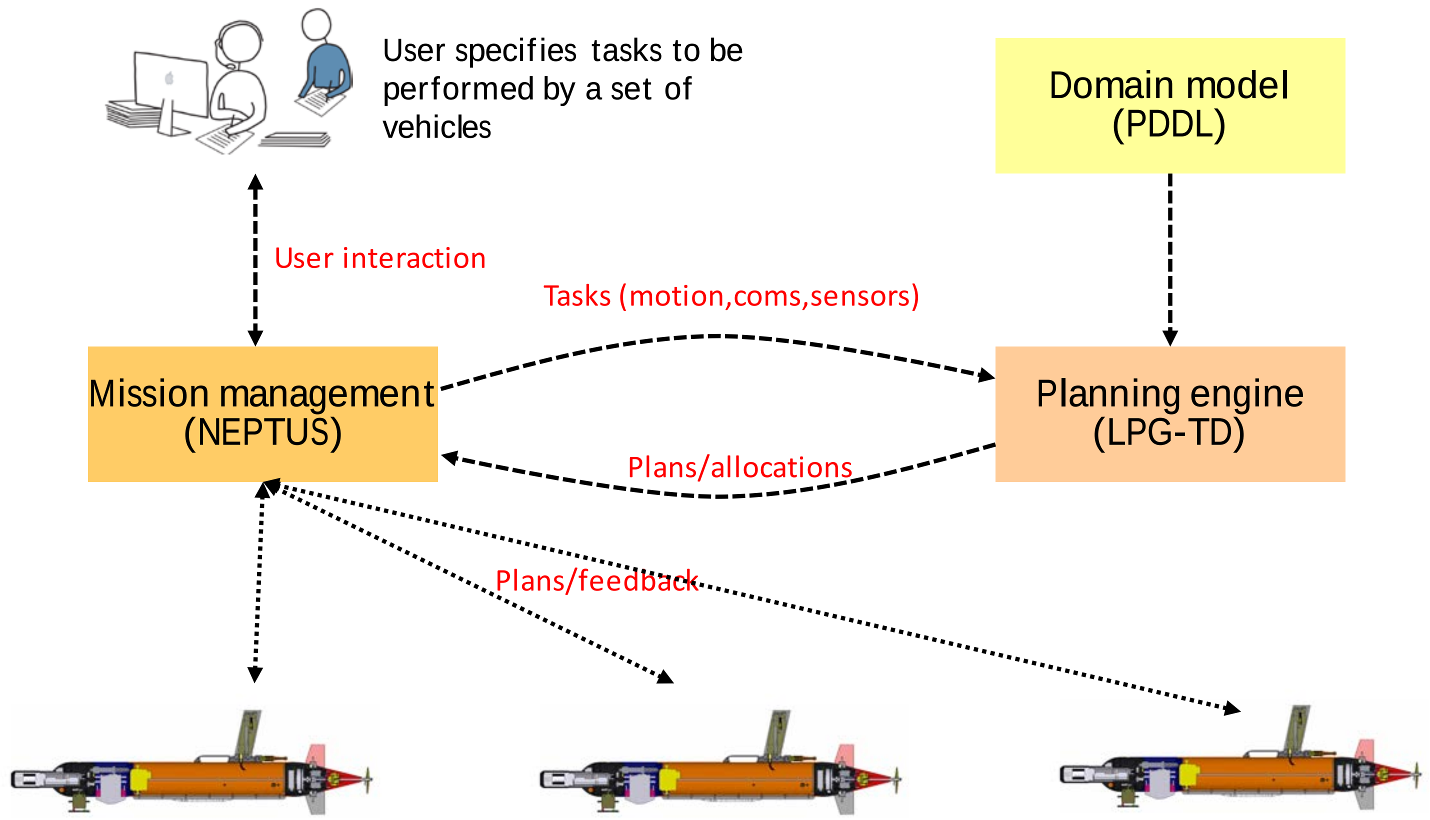




Real time supervision

Runs

Multi-vehicle planning and execution



Lukas Chrpa, José Pinto, Manuel A. Ribeiro, Frederic Py, João Sousa, Kanna Rajan, **“On Mixed-Initiative Planning and Control for Autonomous Underwater Vehicles**”, submitted to IROS 2015.

OPERATIONS

Large scale exercises
Simultaneous ops in the Pacific, Atlantic and Adriatic
Deployments from shore or from ship/submarine
Over 100 days of ops per year

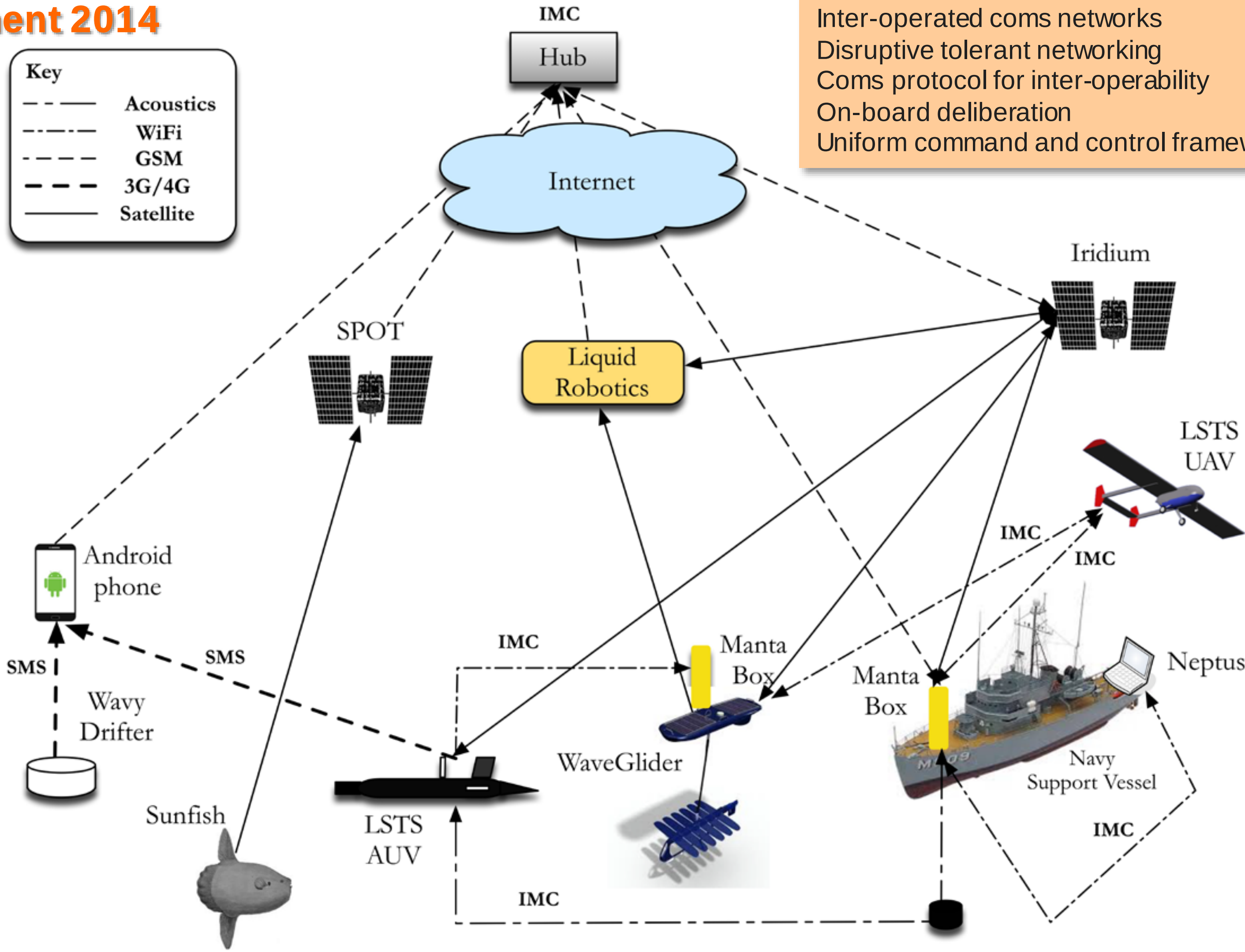
2014

- 1.600 Km underwater
- 200 flights

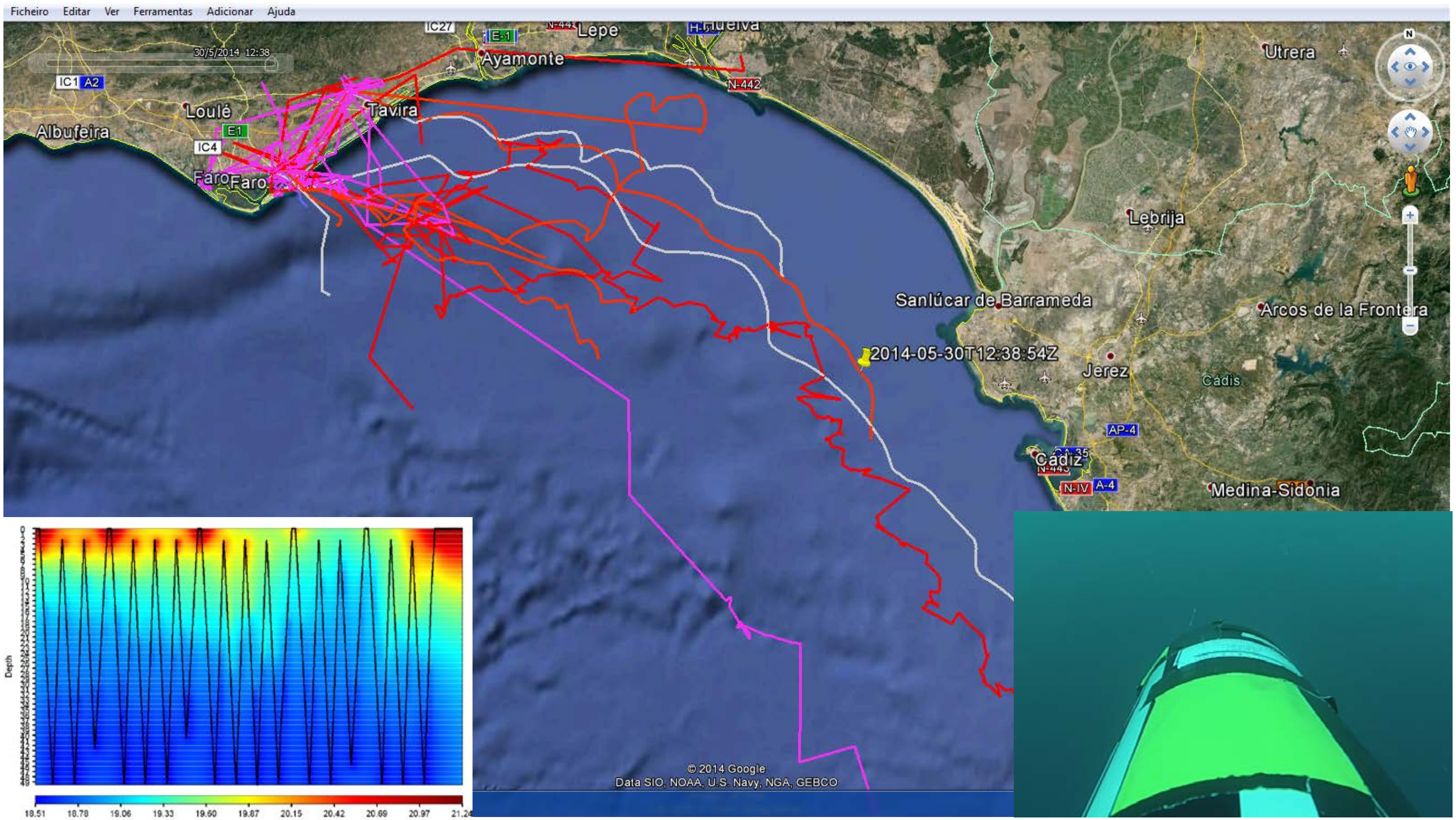
Networked vehicle systems in action

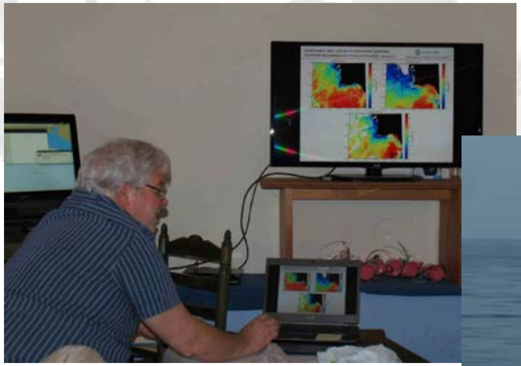
Exercise REP 2014 Atlantic
Sunfish experiment 2014

- Inter-operated coms networks
- Disruptive tolerant networking
- Coms protocol for inter-operability
- On-board deliberation
- Uniform command and control framework



Problem: Learn model of fish behavior from optimal adaptive sampling





LSTS

Vehicles
Tags
Command/Control
Comms

UPCT

Modeling & Data Analysis

NTNU

UAV field experience
Thermal imagery use

Liquid Robotics

CIBIO

Tagging
Biology
Ecological Analysis

IPMA
PO Navy

Ship operations

FEUP

Educational Outreach

MBARI

Deliberative Control
Operational concepts
Inter-disciplinary experience
Large scale field experimentation

REP Atlantic 2014 exercise *July 2014*

Organized by

- PO Navy
- Porto University
- Centre for Maritime Research and Experimentation

Participants

- University of Rome
- Certh
- Royal Institute of Technology
- Evologigs
- OceanScan

Areas

- Mine Warfare
- Harbour Protection
- Expeditionary Hidrography
- Search and Rescue
- Maritime Law Enforcement
- Environmental Monitoring

REP Atlantic 2014 *Resources*

NRP Pegaso (AUVs/UAVs)

NRV Alliance (AUVs, ASVs)

NRP Auriga (AUVs)

NRP Arpão (AUVs)

REP Atlantic 2014 *Resources*


AUV Folaga / CMRE


UAV X8 / LSTS


LAUV seacon class / PO Navy


AUV Ocean explorer / CMRE


LAUV Noptilus class / LSTS

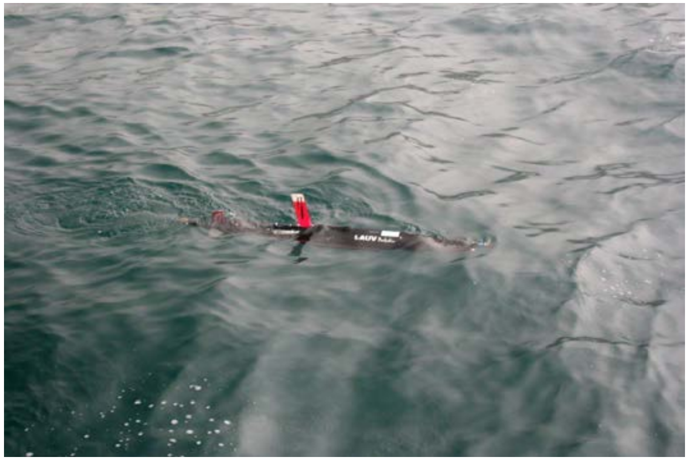

AUV Gavia / PO Navy


ASV Wave glider / CMRE


LAUV Xplore class / FEUP

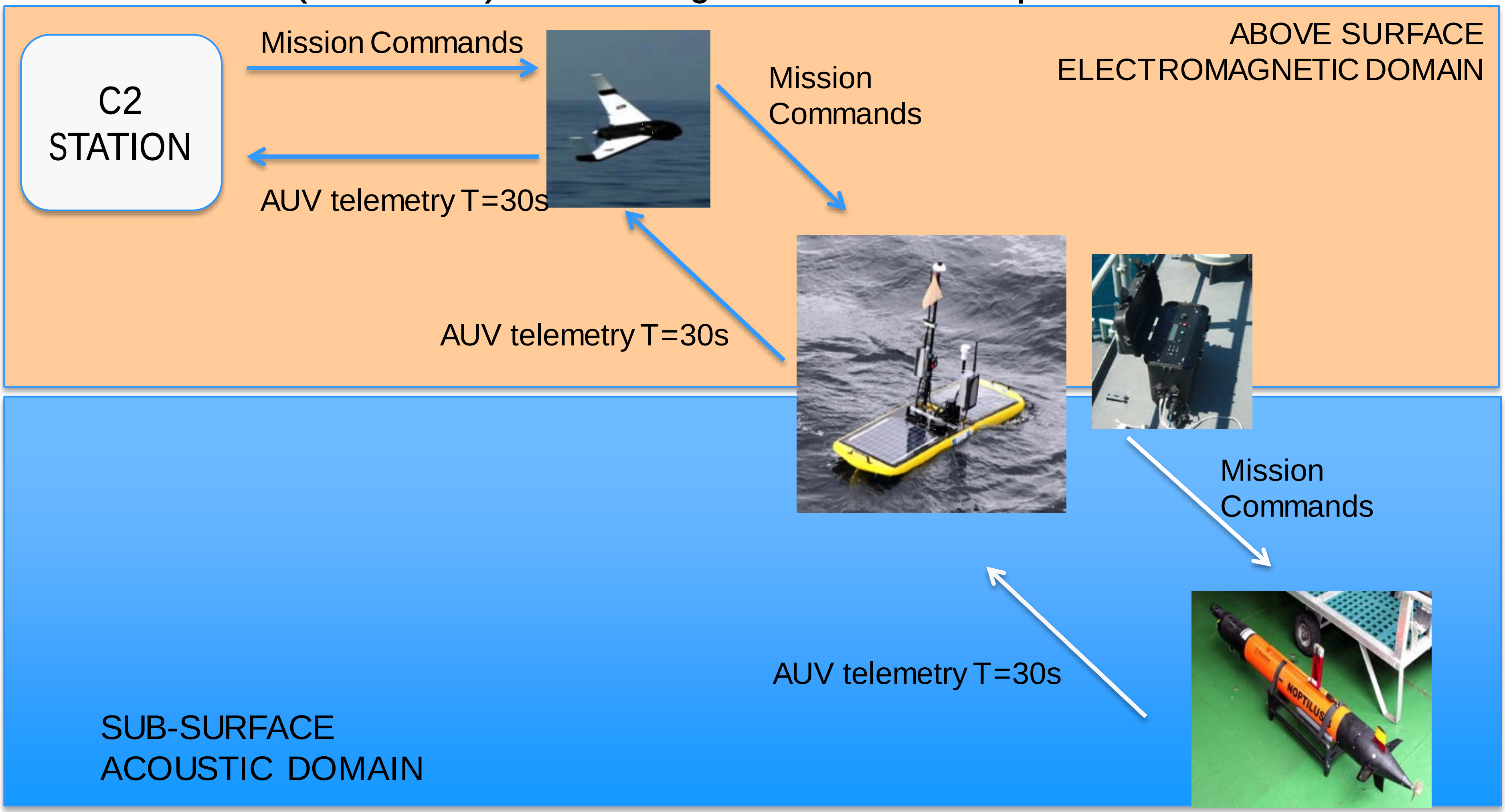
REP Atlantic 14 *Highlights*

“Truly” autonomous UAV/AUV operations
Coordinated observations - coastal fronts
UAVs for “bent” LOS communications
Mixed initiative control ASVs, AUVs, UAVs



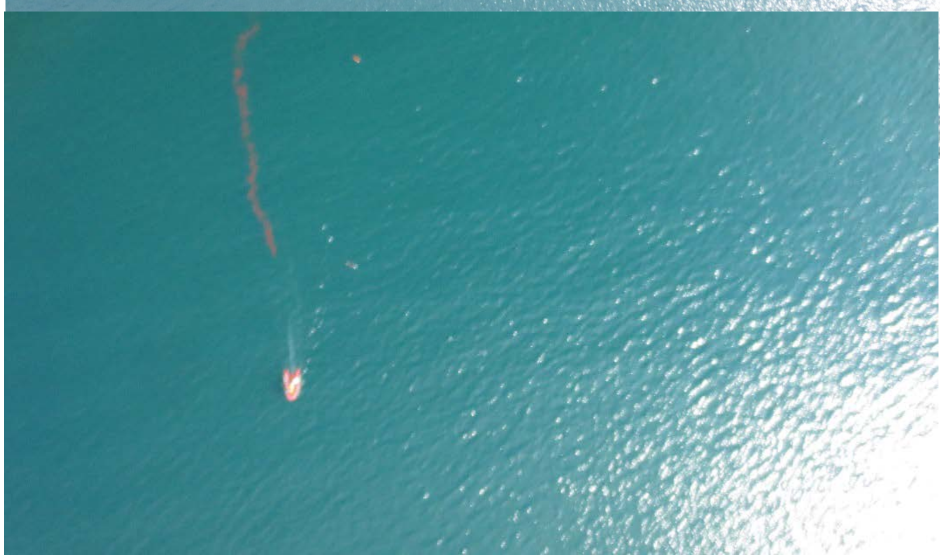
REP Atlantic 14 *Highlights*

UAS controls (feedback) a submerged AUV with help of a Wave Glider



Courtesy of João Alves, CMRE

Coordinated air/ocean observations Split *Sept 2014*



REP Atlantic 2015 exercise *July 2015*

Organized by

- PO Navy
- Porto University
- Centre for Maritime Research and Experimentation
- University of Açores

Participants

- Naval Undersea Warfare Center
- NTNU
- Royal Institute of Technology
- NASA Ames
- OceanScan
- University of Plymouth

Areas

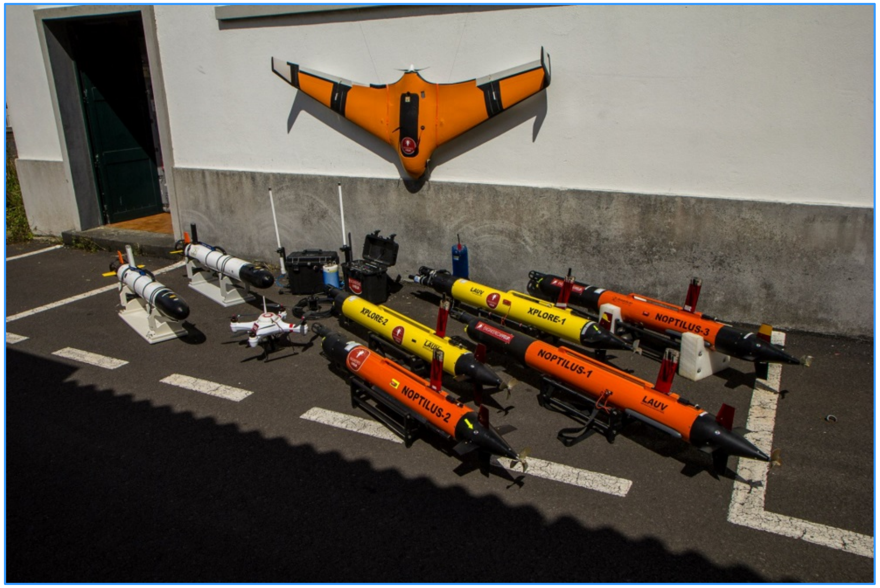
- Mine Warfare
- Harbour Protection
- Mapping termal vents
- Eco systems mapping
- JAUS enabled UAV/AUV interaction
- Tracking whales and charactering environmental parameters

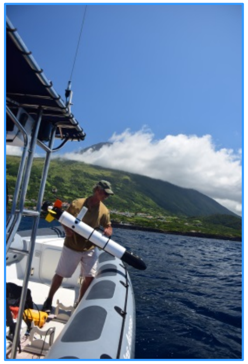
REP Atlantic 2015 *Resources*

NRP Almirante Gago Coutinho

U of Açores R/V Aguas Vivas

LSTS and NORUT X8s





NUWC Iver2s

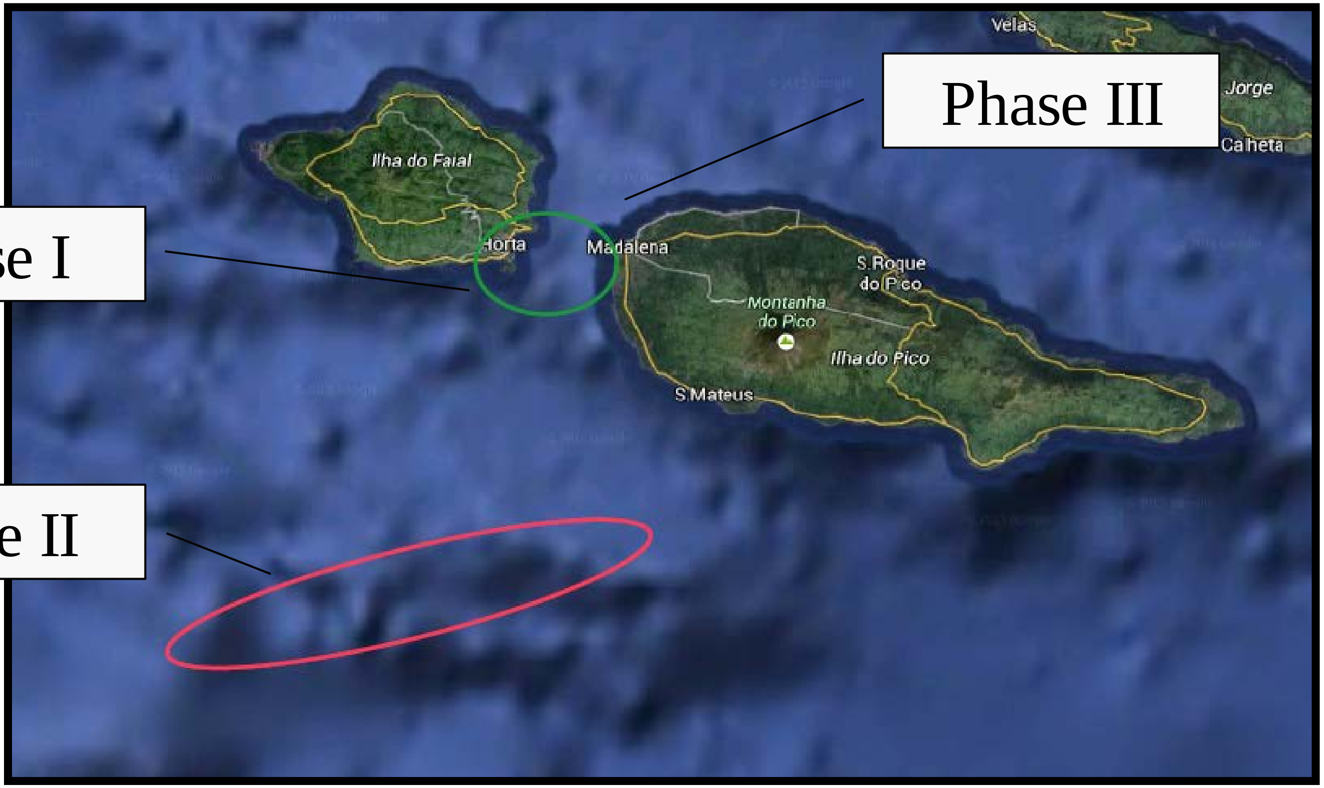
LSTS LAUVs

REP Atlantic 2015 *Op areas*

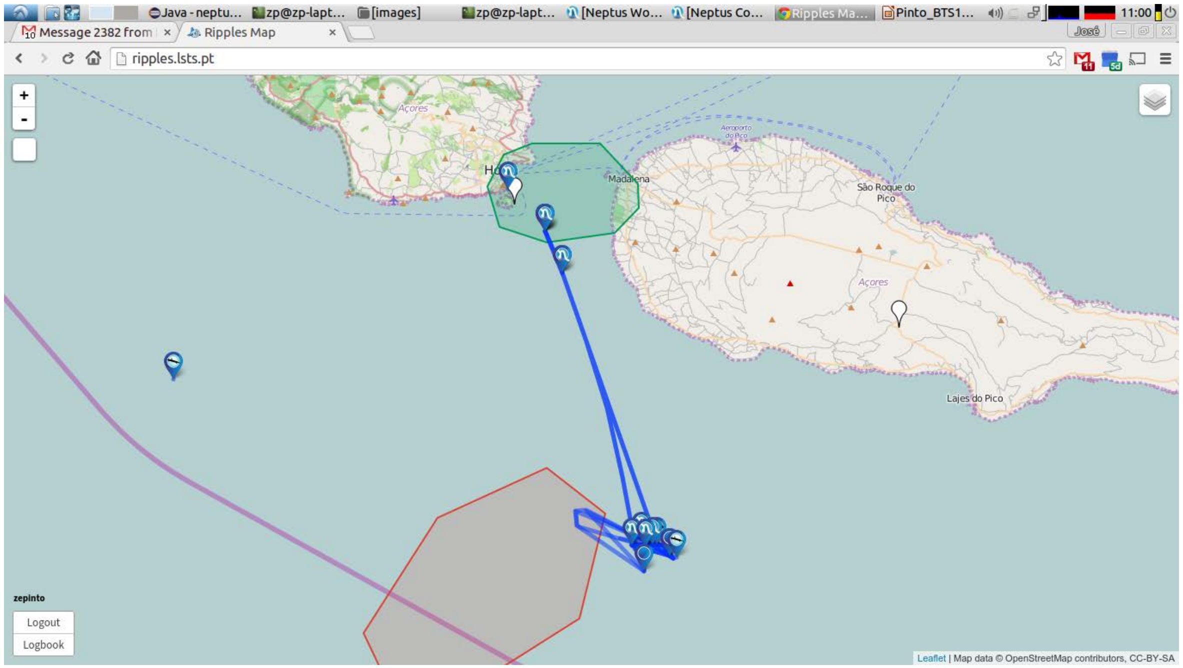
Phase I

Phase II

Phase III



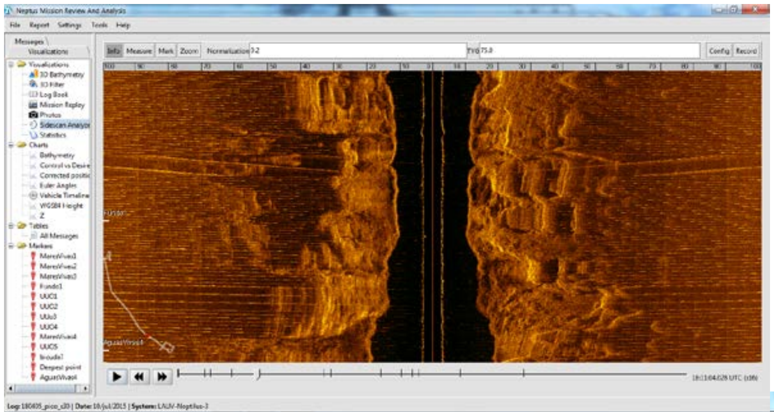
REP Atlantic 2015 *Remote operations*

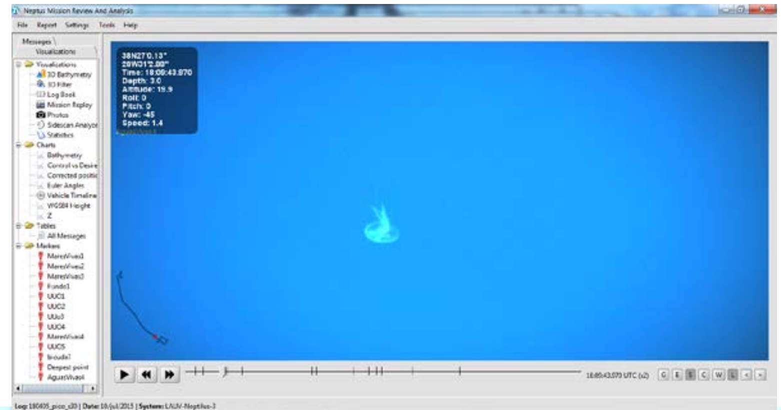


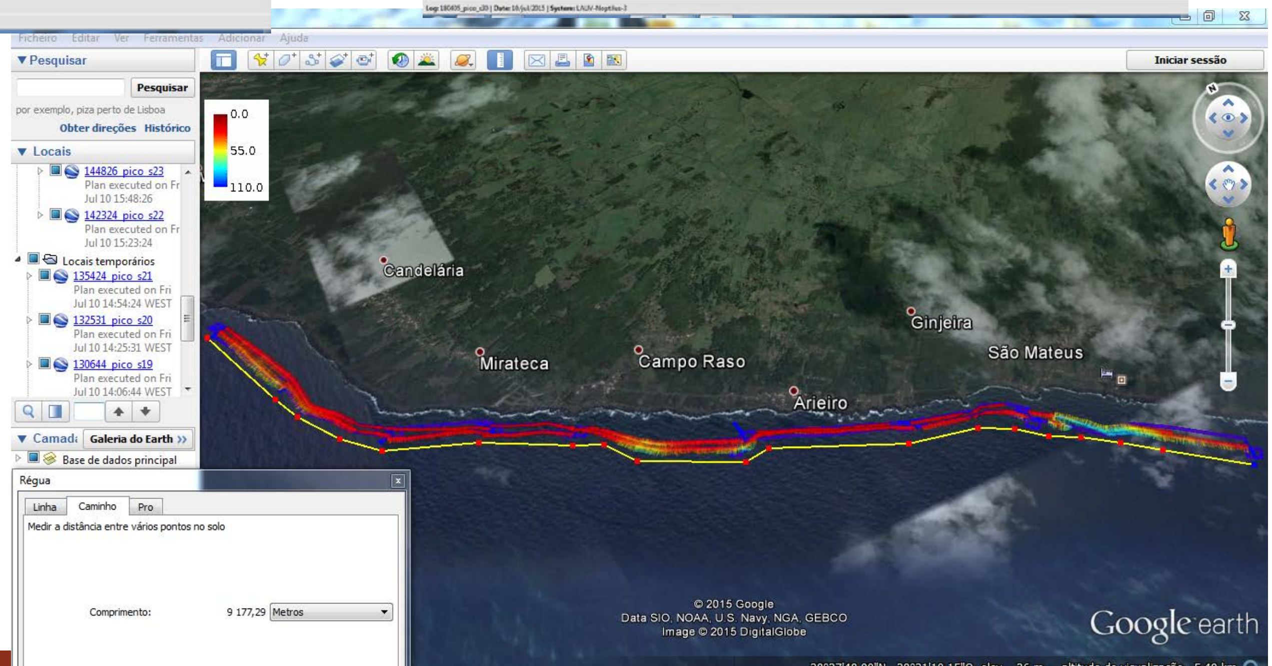
Web viz
Integration with NASA MTS

REP Atlantic 2015 *Highlights*

- Mapping marine ecosystems with AUVs and UAVs (hyperspectral)







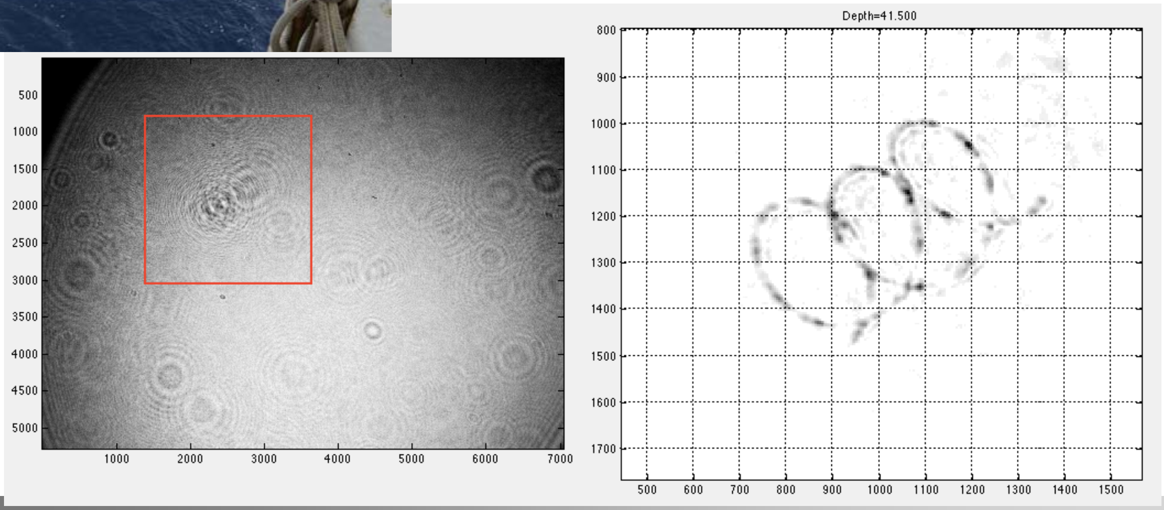
REP Atlantic 2015 *Highlights*

- UxV communication with JAUS messaging standard to support hybrid platform network
  - Iver2 – NUWC
  - X8 - LSTS

REP Atlantic 2015 *Highlights*

- Tracking whales for environmental characterization with AUVs (CTD/HOLO/Fluorometer) and UAVs (IR/Hyperspectral)

Holo prototype developed by Alex S, University of Plymouth




CONCLUSIONS

- Systems of physical and computational entities with coupled physical and computational dynamics
- Compositional dynamic structure delivers novel system level properties that cannot be found in the constituent entities
- Interdisciplinary research
- Collaborative experimentation
- Interoperability frameworks
- Open software