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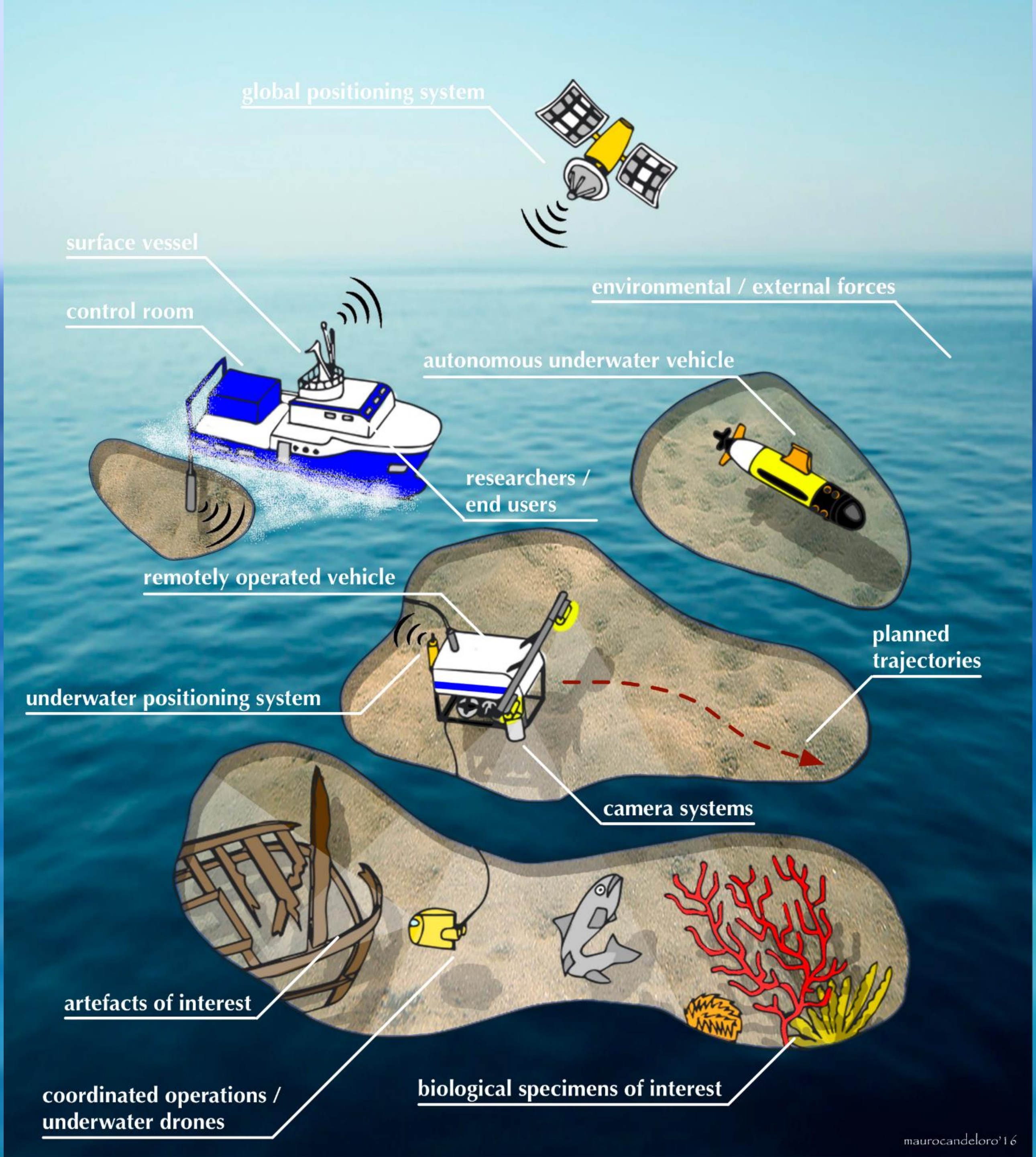
Centre for Autonomous Marine Operations and Systems

Tools and Methods for Autonomous Operations on Seabed and Water Column using Underwater Vehicles

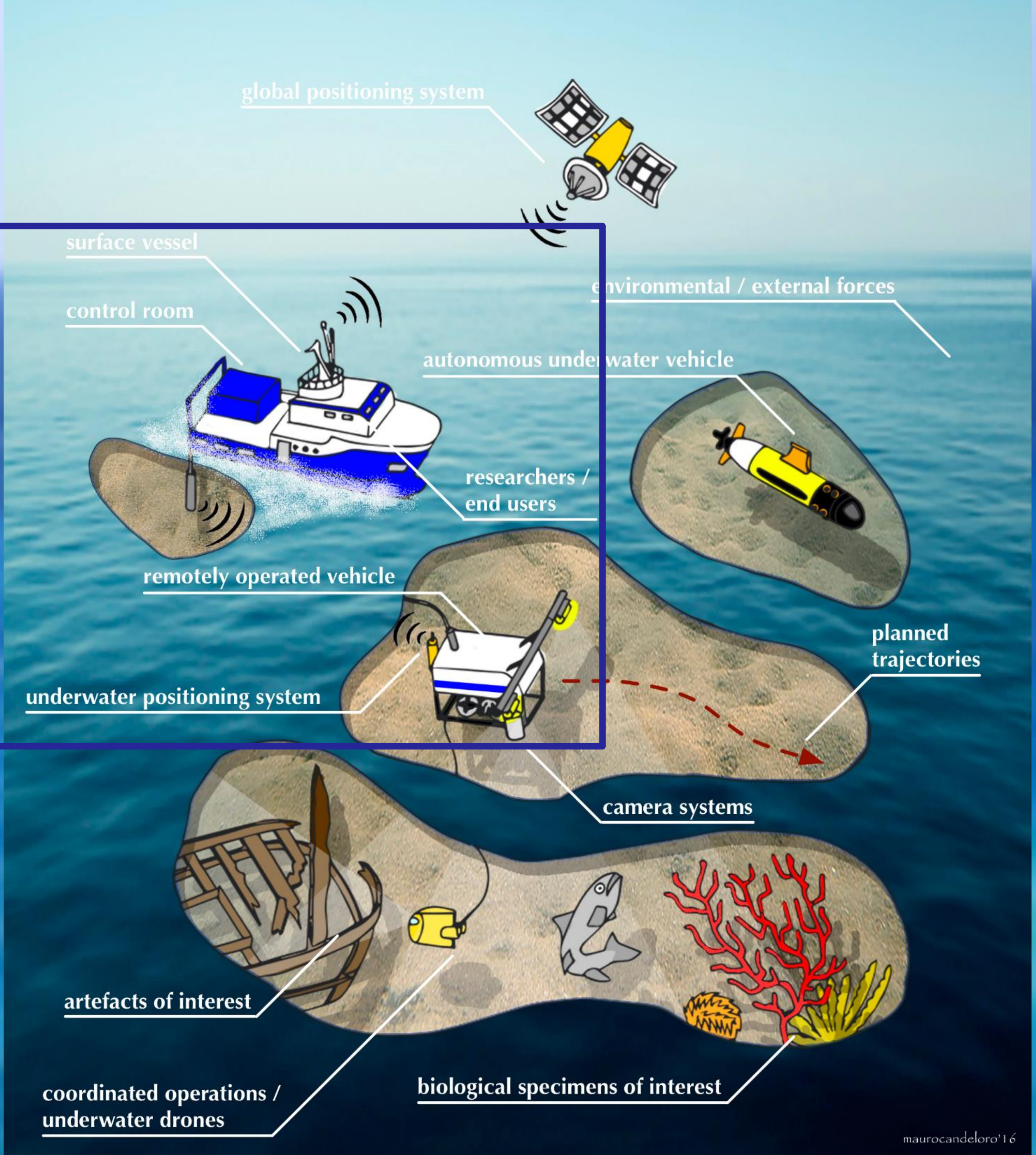
Mauro Candeloro

Submitted PhD Thesis

Centre for Autonomous Marine Operations and Structures (**AMOS**),
NTNU, Trondheim, Norway

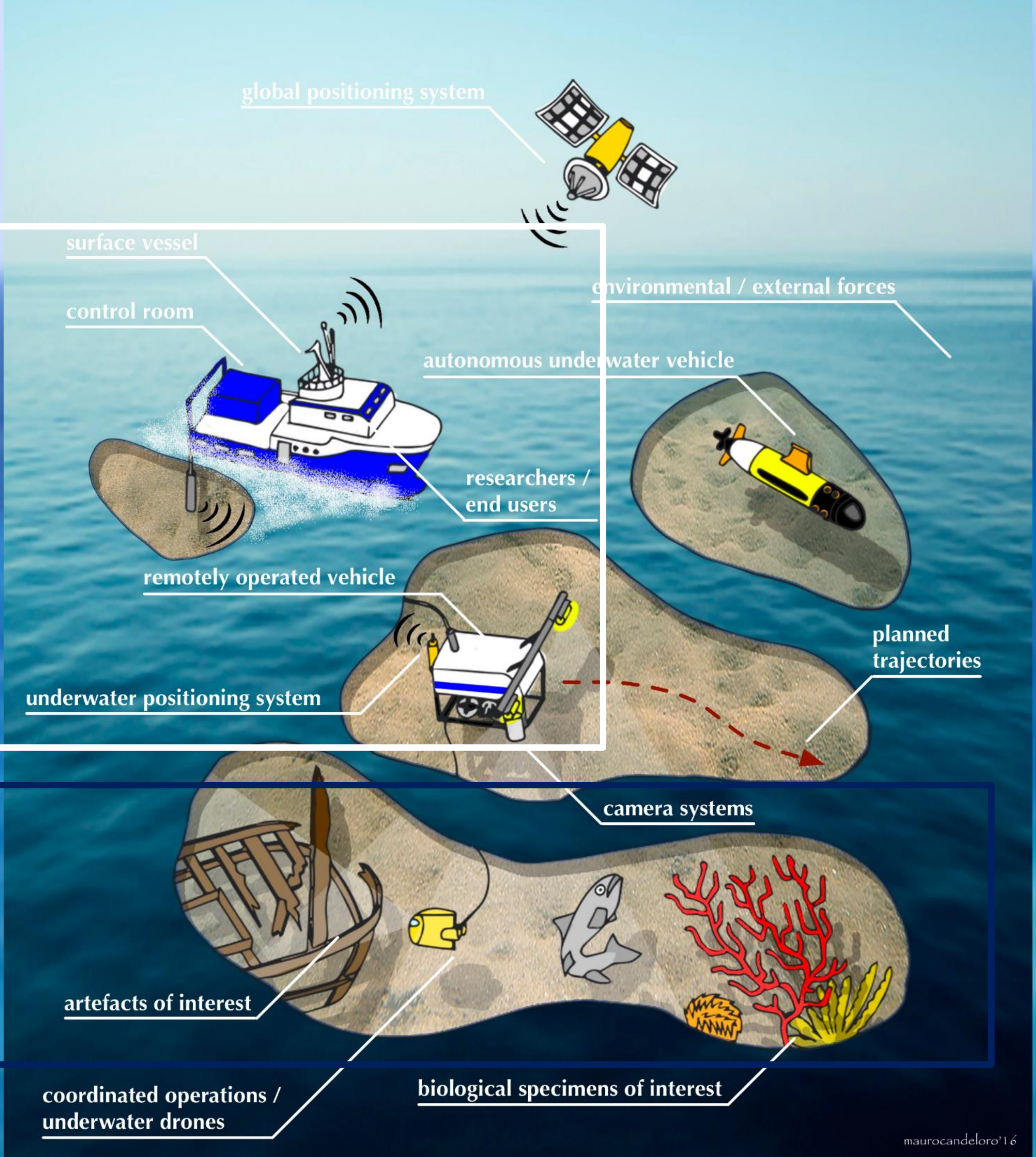

global positioning system
surface vessel
control room
environmental / external forces
autonomous underwater vehicle
researchers / end users
remotely operated vehicle
planned trajectories
underwater positioning system
camera systems
artefacts of interest
coordinated operations / underwater drones
biological specimens of interest
maurocandeloro'16

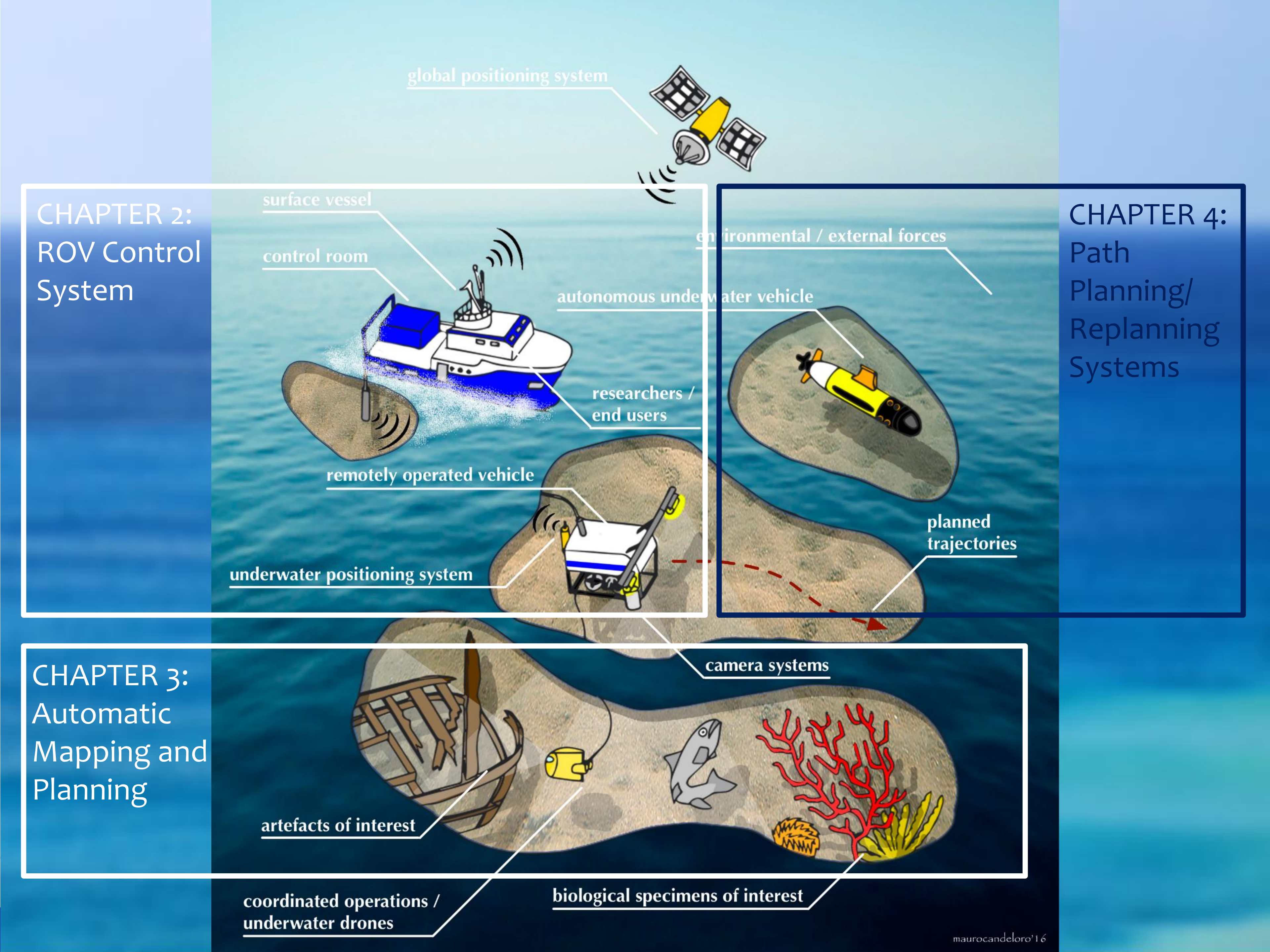
CHAPTER 1: ROV Control System



CHAPTER 1: ROV Control System

CHAPTER 2: Automatic Mapping and Planning





CHAPTER 2: ROV Control System
CHAPTER 4: Path Planning/ Replanning Systems
CHAPTER 3: Automatic Mapping and Planning
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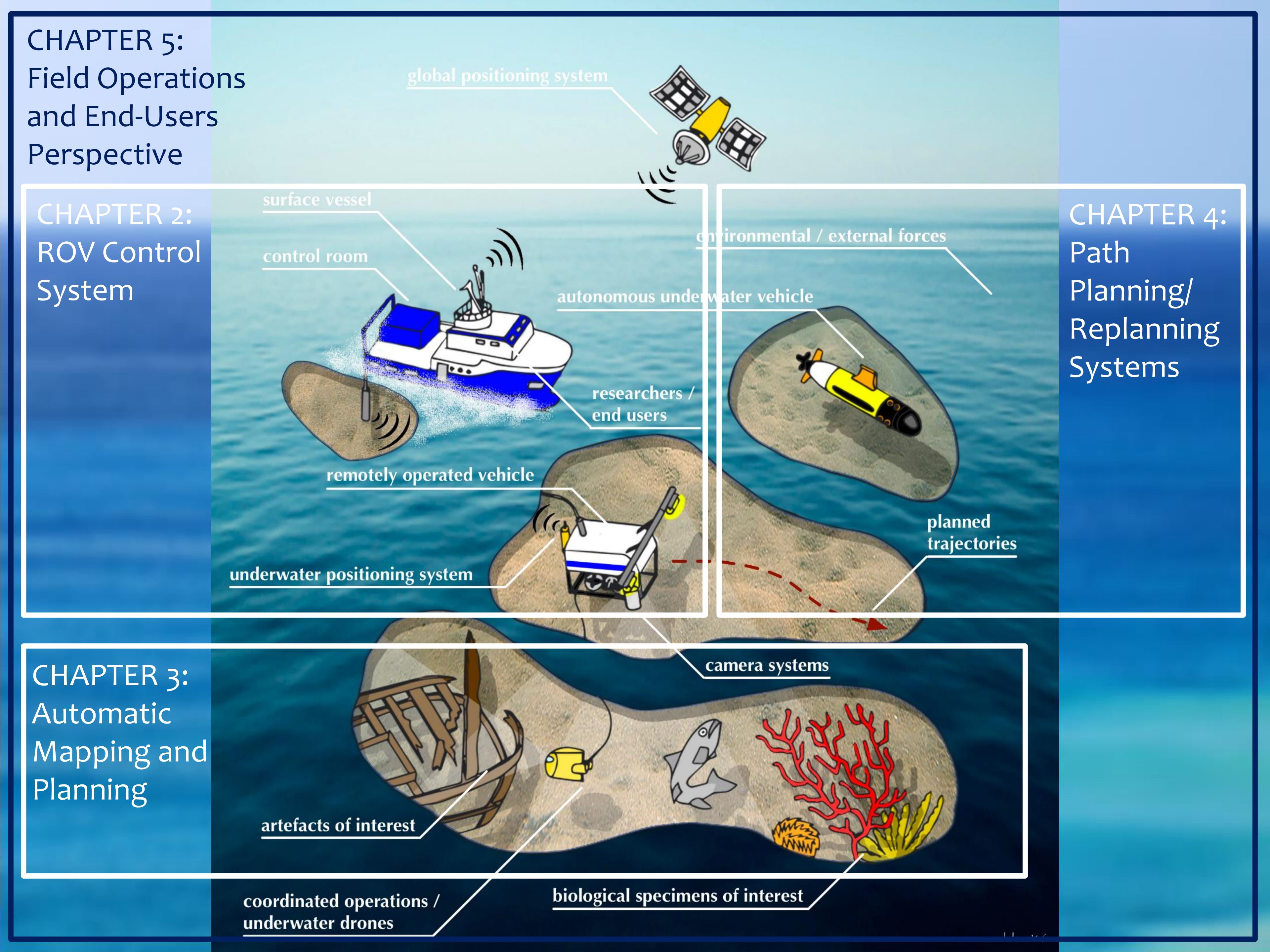
CHAPTER 5:
Field Operations and End-Users Perspective
CHAPTER 2:
ROV Control System
CHAPTER 4:
Path Planning/ Replanning Systems
CHAPTER 3:
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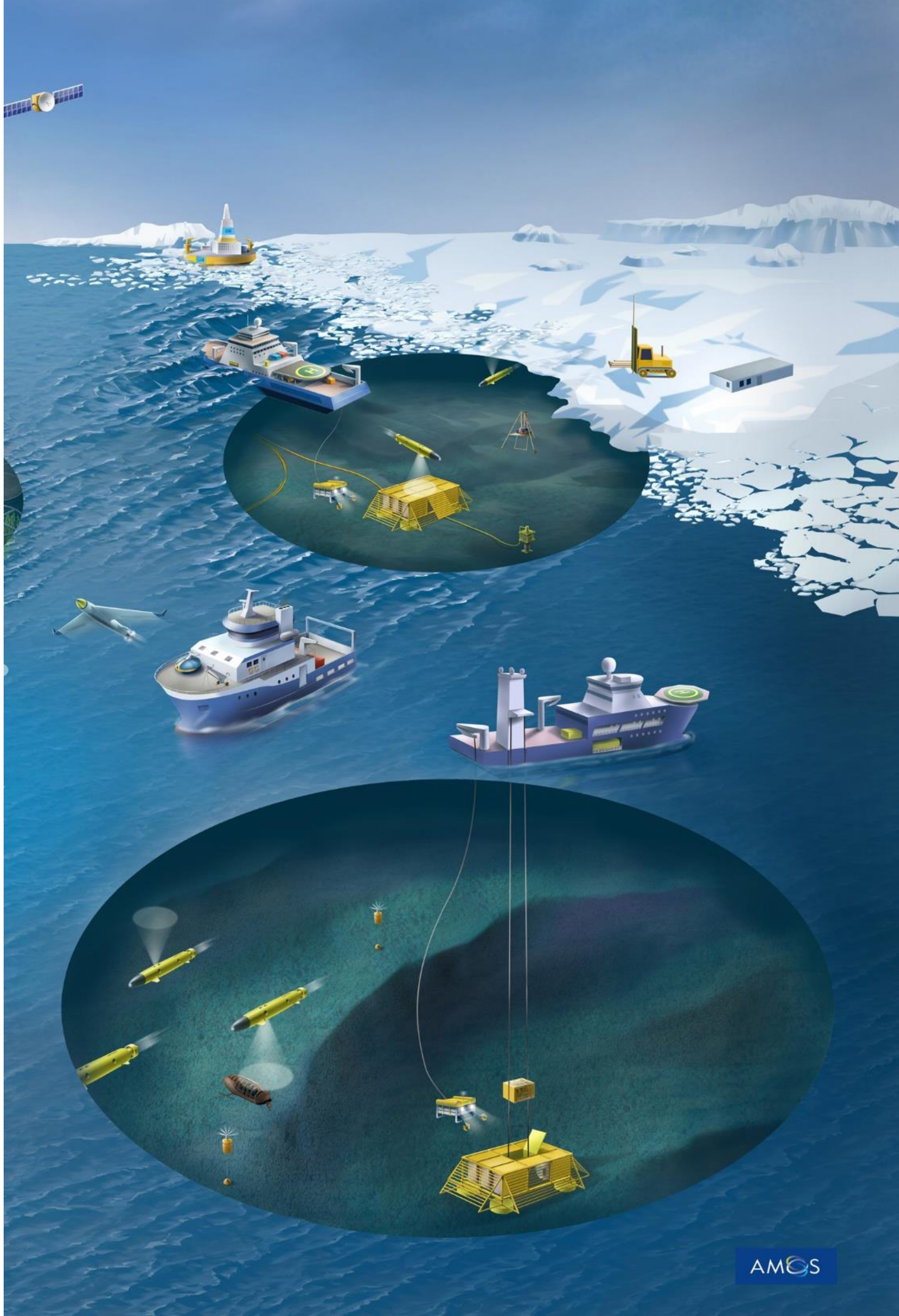
From CHAPTER II:

HMD as a new Tool for Telepresence in Underwater Operations and Closed-Loop Control of ROVs

Mauro Candeloro , Eirik Valle, Michel R. Miyazaki, Roger Skjetne ,
Martin Ludvigsen, Asgeir J. Sørensen

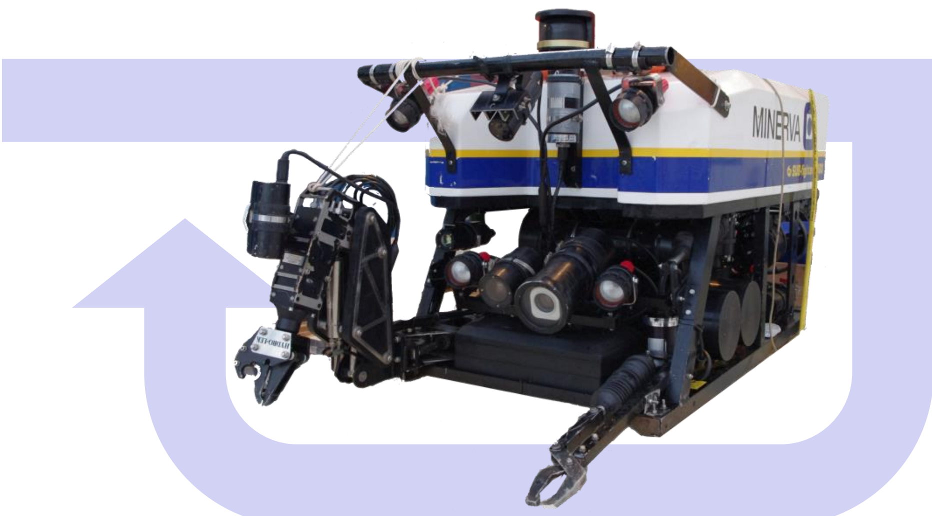
Centre for Autonomous Marine Operations and Structures (**AMOS**),
NTNU, Trondheim, Norway

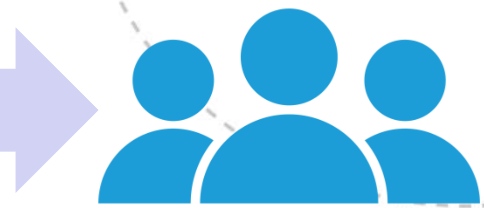
- Goal, definitions and history of HMDs
- Integration with DP system
- Experimental results



Goal

Head Mounted Displays (HMDs) are becoming a popular tool to improve users experience and efficiency in many fields.





Use HMD to improve the telepresence experience and situational awareness during underwater operations.

Use HMD to actively control a Remotely Operated Vehicle (ROV).

Three guidance methods involving the usage of HMIs have been developed.
Preliminary full-scale experiments and conclusions on the usability

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Benefits

A Head (or Helmet) Mounted Display (HMD): a device containing one or more displays that is attached to the head (or the helmet) of an operator.

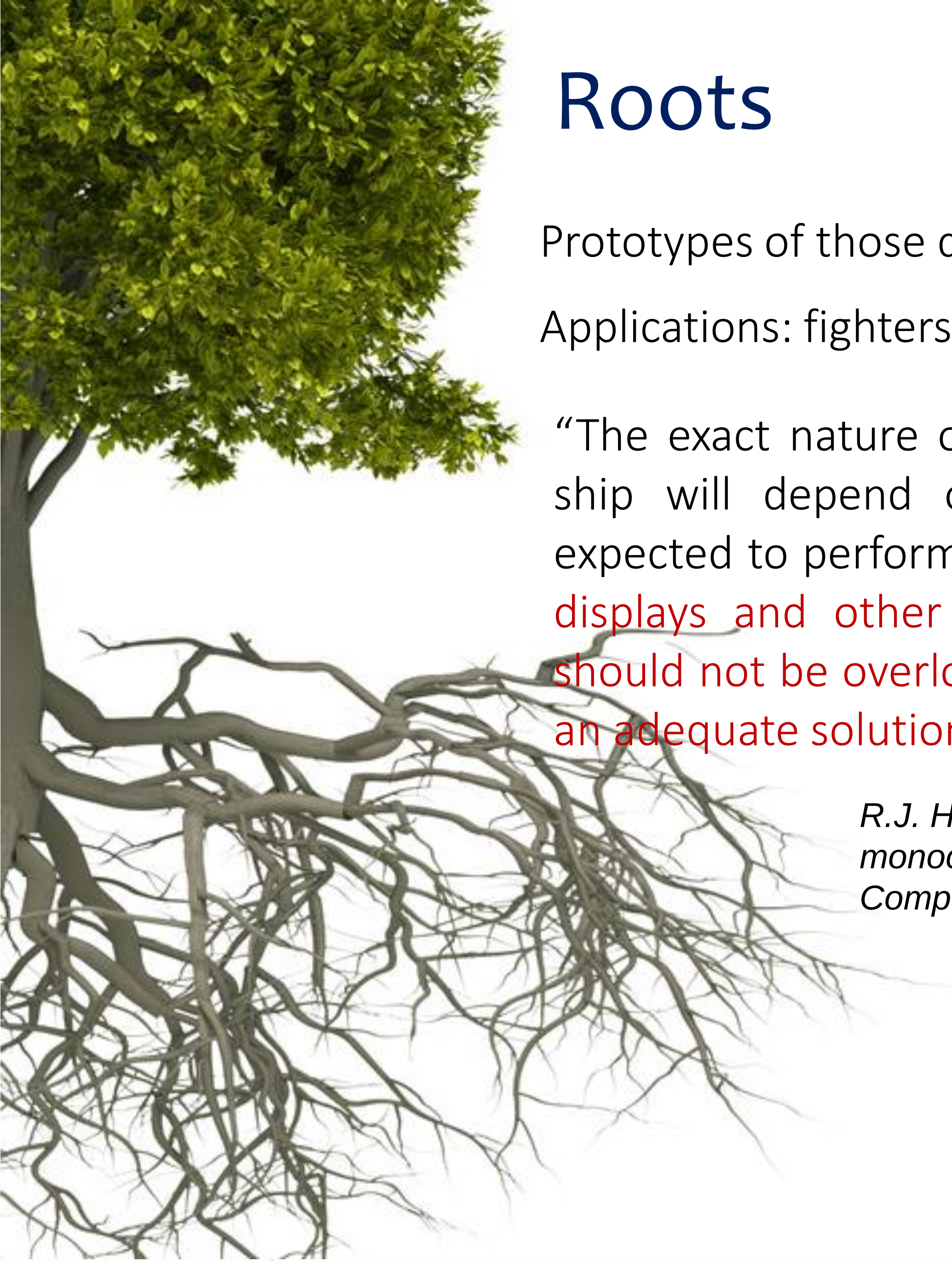
Stereoscopic view

Depth feeling

Immersive experience

First person perspective


JVC
MONTH DAY YEAR PM HOUR MIN
OCT 26 1985 09 00
DESTINATION TIME
MONTH DAY YEAR PM HOUR MIN
OCT 21 2015 07 28
PRESENT TIME



Roots

Prototypes of those devices have their roots back in the 60s.

Applications: fighters / space ships…

"The exact nature of the visual displays utilized in a space ship will depend on precisely what operations man is expected to perform [during] a given mission [...]. Nonlinear displays and other relatively novel display characteristics should not be overlooked or neglected in attempting to find an adequate solution to... [such problems]."

R.J. Hall and J.W. Miller. Feasibility study for a monocular headmounted display. Hughes Aircraft Company, Special Technical Document SD 60-70, 1960.

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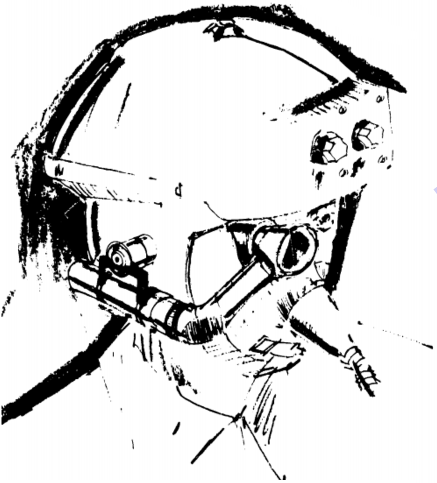
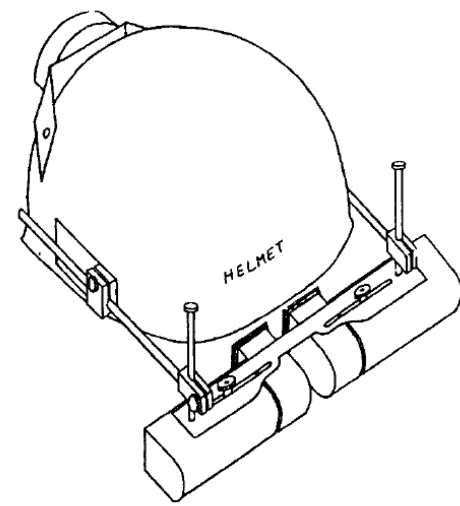
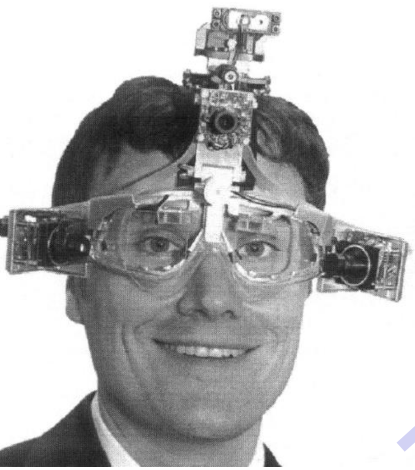




[1962] Head-mounted electronic device allows viewing two images at once

[1988] Helmet Mounted Display for Telerobotics

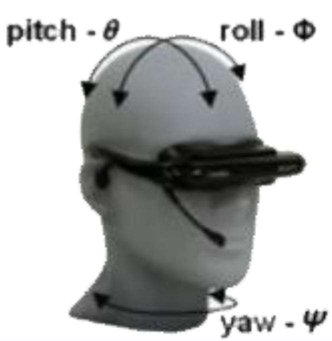
[2006] Head-Mounted camera for medical documentation



[2014] Remote control system using head tracker system

[2014] 3D teleoperation of field robots

[2015] Videogaming and Virtual Reality




blueye

Extending the Human-Machine interaction possibilities

Could it represent a valid alternative to the classical joystick approach?

The development is aiming to create an easier and more intuitive interface, that could be also used by the technology end-users, such as archaeologists or biologists.

AUR-Lab operations

- manipulation work, picking operations, sensor deployment operations (manipulator operator needed)
- survey, mapping and exploration

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Oculus Rift

Stereo-camera system

- Two Allied Vision GC1380C
- Resolution of 1360X1024 pixels
- Frame rate of 20.2fps


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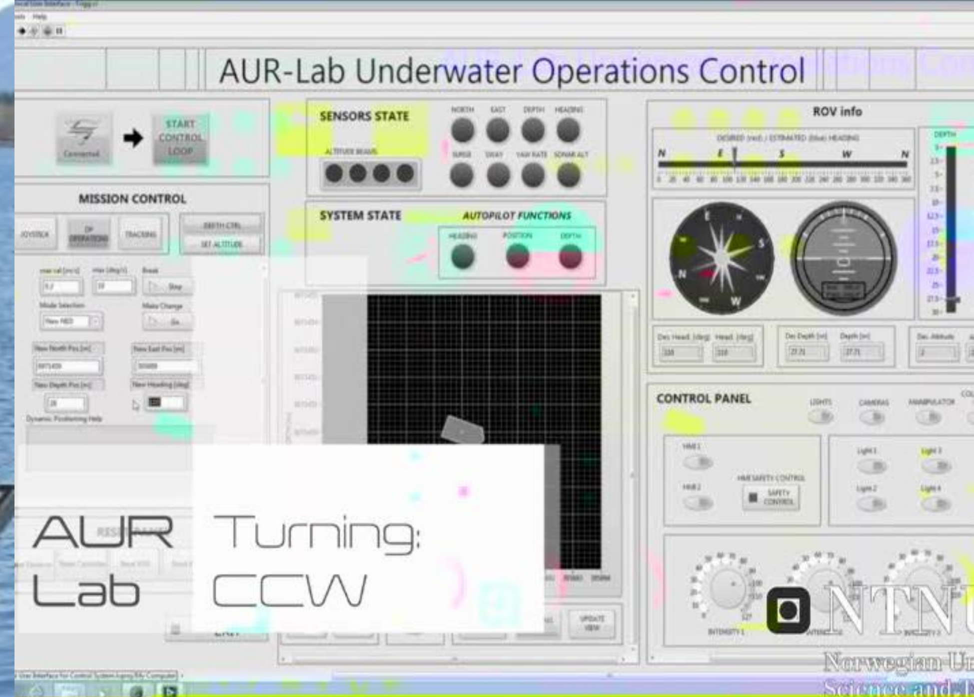
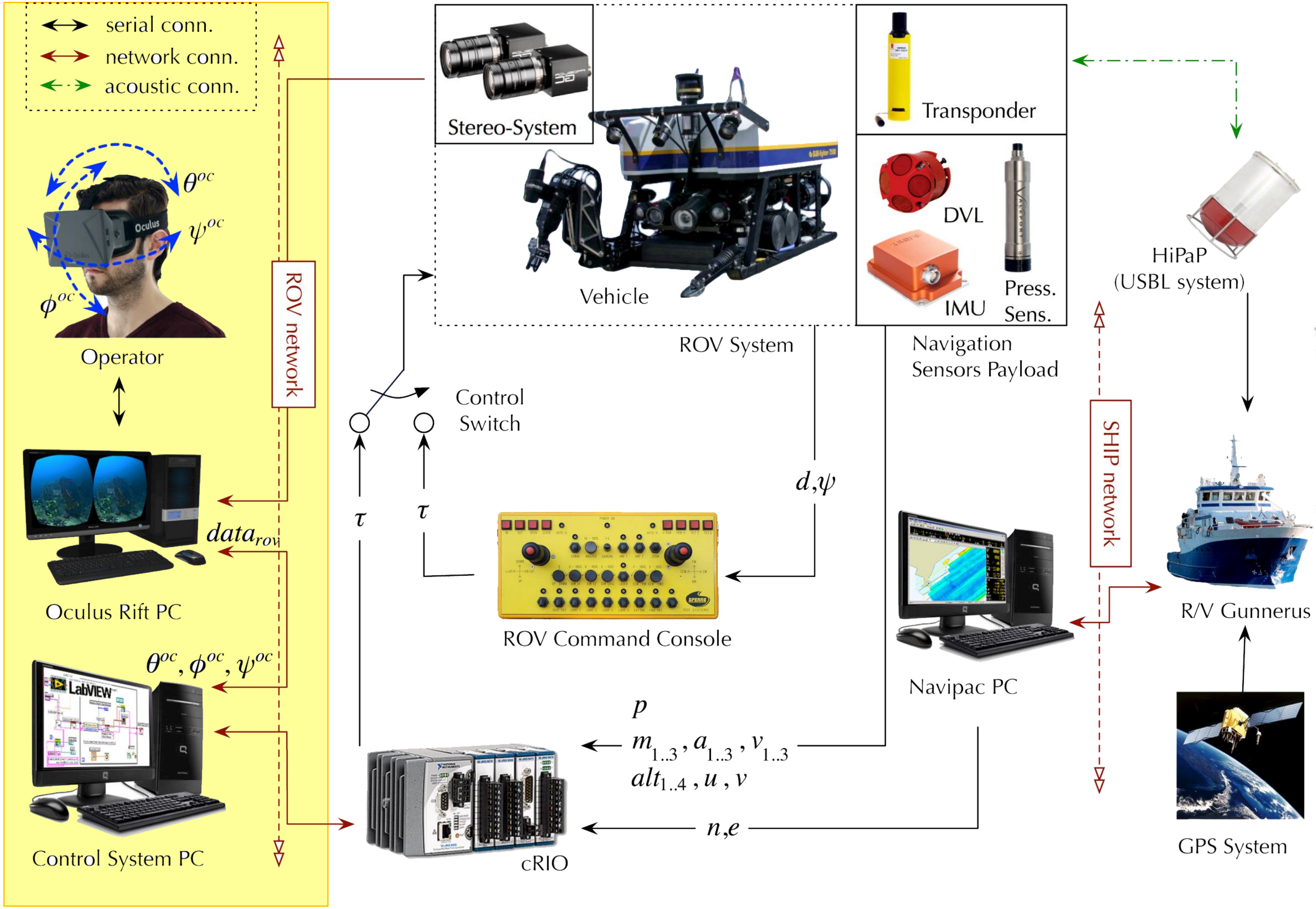
SUB-fighter 30k


AUR-Lab Underwater Operations Control
START CONTROL LOOP
SENSORS STATE
SYSTEM STATE
AUTOPILOT FUNCTIONS
MISSION CONTROL
ROV info
CONTROL PANEL
AUR Lab
Turning: CCW
NTNU


Video Speed 2X
NTNU


serial conn.
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acoustic conn.
θ^{oc}
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Operator
ROV network
Oculus Rift PC
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Control System PC
Stereo-System
Vehicle
ROV System
Transponder
DVL
IMU
Press. Sens.
Navigation Sensors Payload
HiPaP (USBL system)
Control Switch
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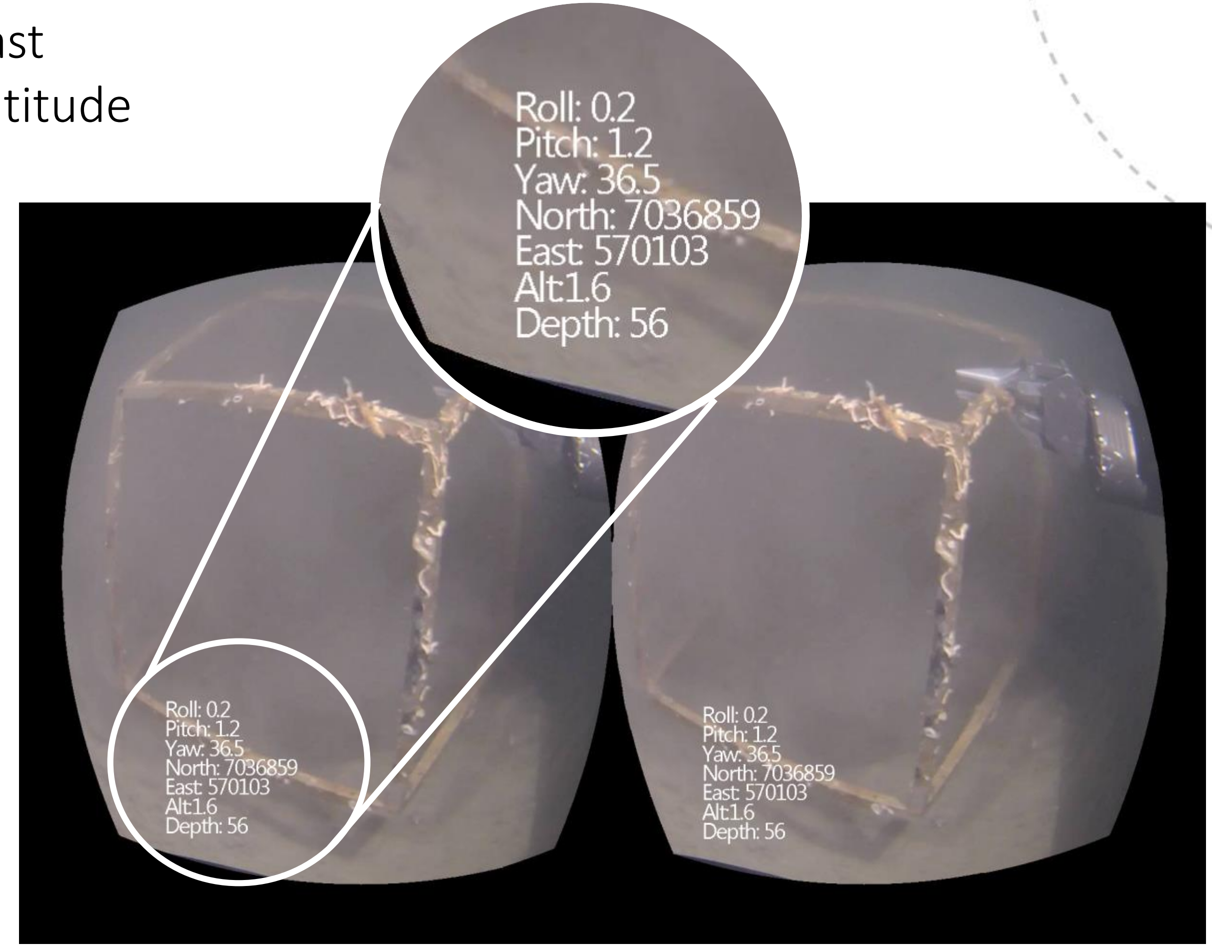
τ
d,ψ
ROV Command Console
SHIP network
R/V Gunnerus
Navipac PC
p
$m_{1..3}, a_{1..3}, v_{1..3}$
$alt_{1..4}, u, v$
n,e
cRIO
GPS System

"Augmented reality" given by navigation information displayed on the HMD images:

- Attitude
- North/East
- Depth/Altitude



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Inside the control room

- Media interest (Discovery Channel Canada)

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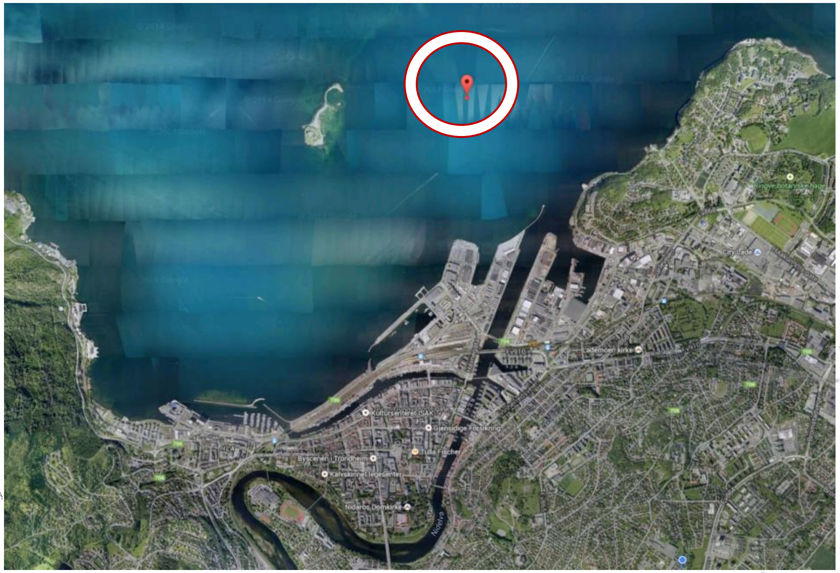
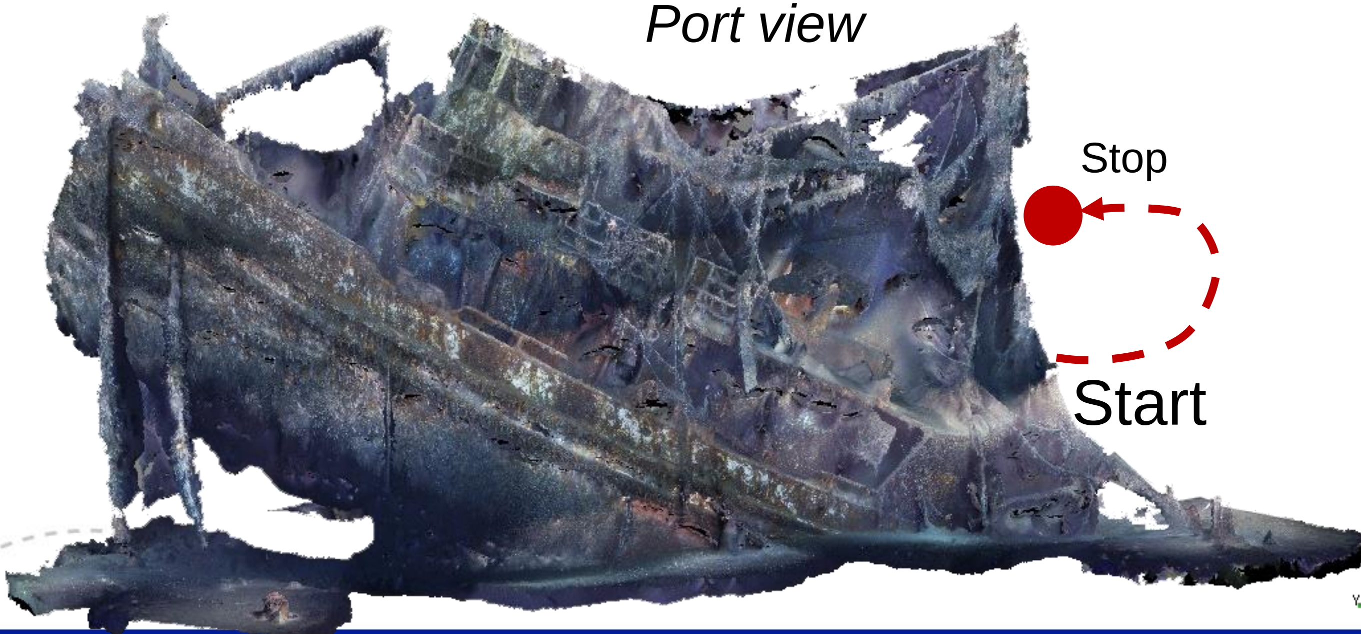
Position control: inspection task



Starboard view
Port view



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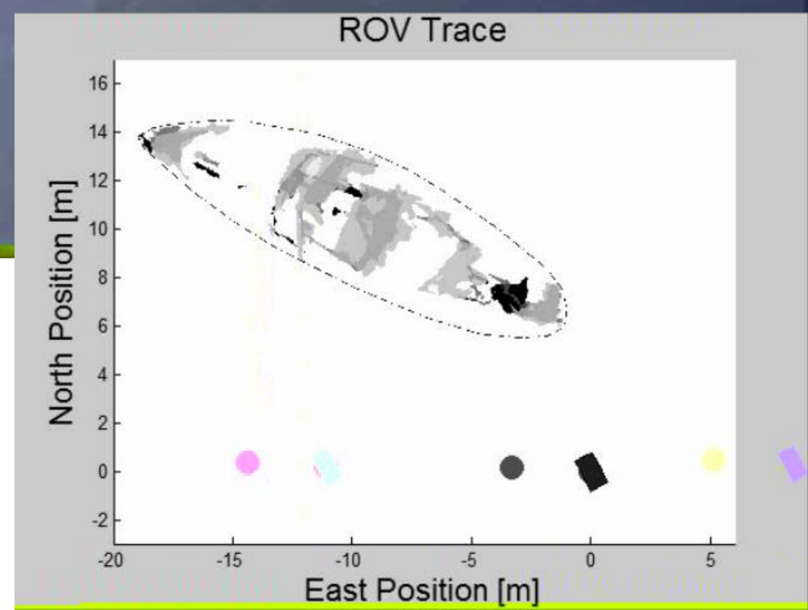

Video Speed 8X

Standard Manipulation Operations

Oculus Rift (one-man) Operations

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Manipulation task

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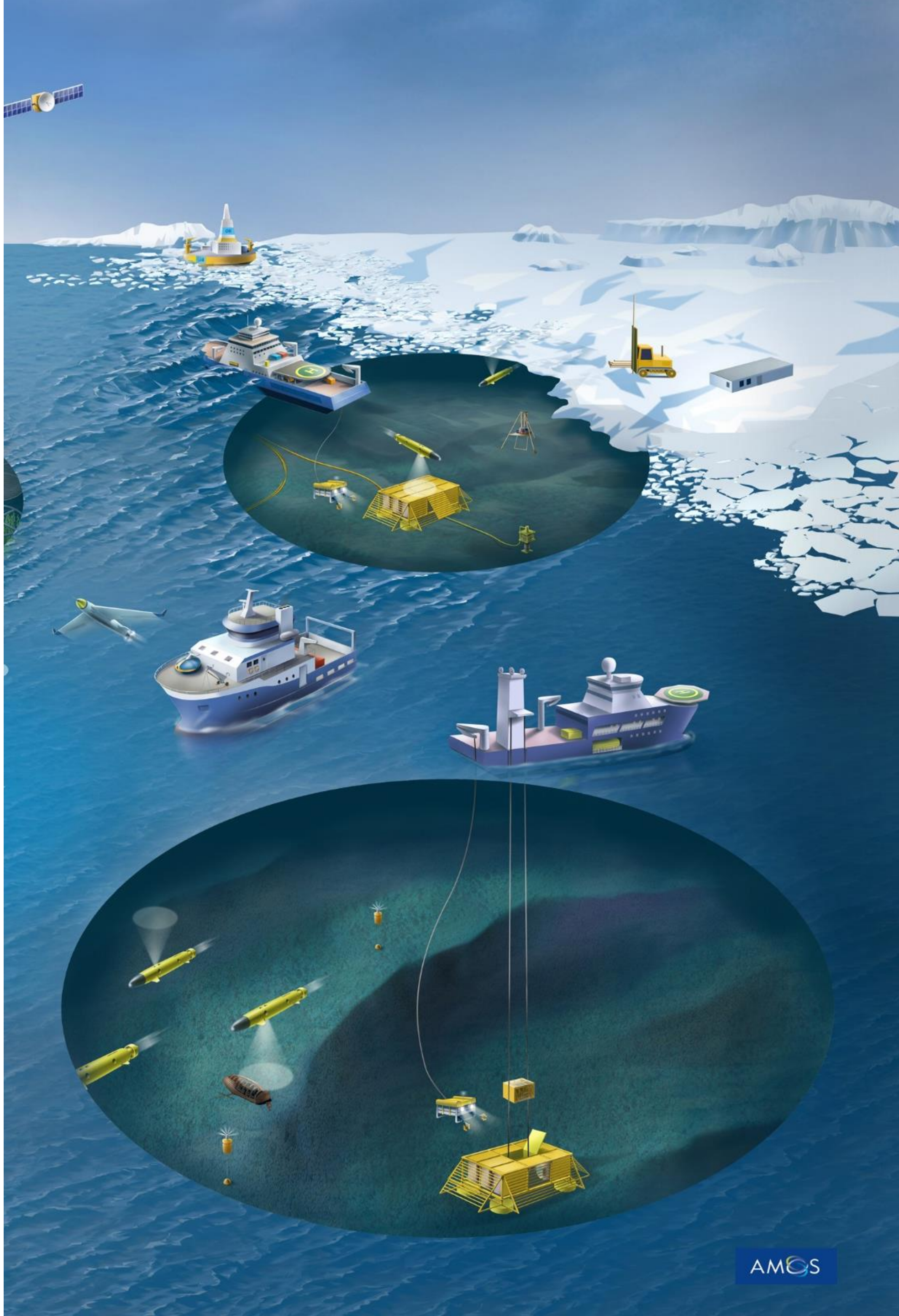
From CHAPTER IV:

A 3D Dynamic Voronoi Diagram-Based Path-Planning System for UUVs

Mauro Candeloro, Anastasios M. Lekkas,
Jeevith Hegde, Asgeir J. Sørensen

Centre for Autonomous Marine Operations and Structures (AMOS),
NTNU, Trondheim, Norway

- Intro: Path Planning & Subsea IMR Operations
- 3D Path Planning Example
- Safe Navigation Rules



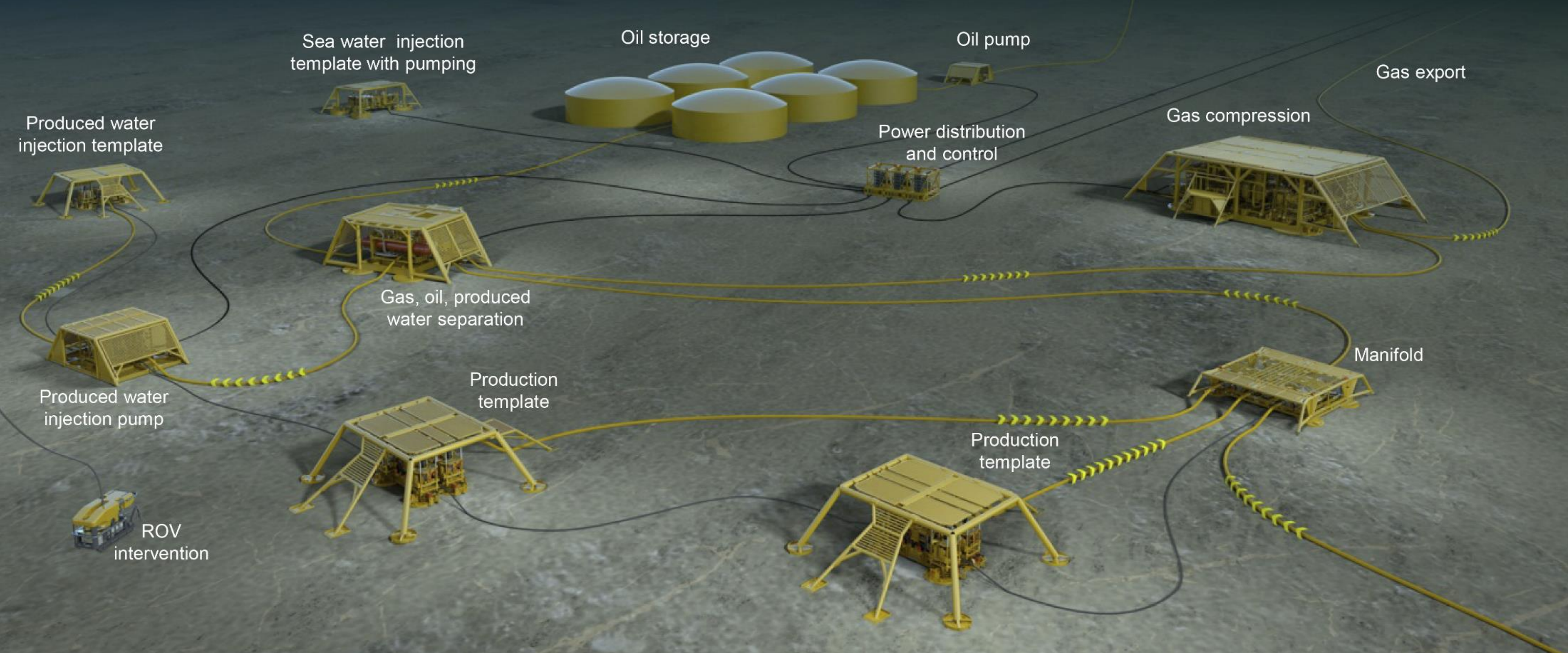
Subsea IMR Operations

Numerous Subsea Production Systems (SPS) have been developed and installed on the seabed to recover hydrocarbons from subsea reservoirs.

Those infrastructures require underwater vehicles to:

- perform operational work on them (act on valves/detach-attach elements..);
- Inspection, Maintenance and Repair (IMR) operations.

Those operations are usually carried on with the support of surface vessels and operators.



Future of SPS

Underwater factories will be operated more and more autonomously, thanks to new underwater infrastructures and advanced vehicles.

Increased Vehicles Autonomy

Permanent Docking Stations

New Underwater Vehicles

Economical Advantages

Notice that the Åsgard gas field (Norway) is the first subsea factory which can process and transport hydrocarbons directly to land without assistance of support vessels.
IMR operations still require assistance.

Roots of the Problem

Path and mission planning is one of the main challenges to face to achieve an higher level of autonomy

"Automation of planning processes has been a central problem in the field of artificial intelligence for more than 30 years [...]."

Watson, D.P., Scheidt, D.H., 2005. Autonomous systems.

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Previous Work

[1] Path Planning System for USV → [2] Path Replanning System for USV → [3] Path-Planning and Replannign system for UUVs

[1] Candeloro, M., Lekkas, A.M., Sørensen, A.J., Fossen, T.I. [2013].
Continuous Curvature Path Planning using Voronoi diagrams and Fermat's spirals.

- Path-planning algorithm targeting USVs (2D planner)
- Real maps covering wide areas are considered
- Fixed obstacles
- Clearance constraints

[2] Candeloro, M., Lekkas, A.M., Sørensen, A.J. [2016].
A Voronoi-Diagram-Based, Dynamic Path-Planning System for Marine Underactuated Vessels.

- Additional depth constraints to avoid grounding
- Obstacle detection and identification methods
- Real-time replanning and simulations.

[3] Candeloro, M., Lekkas, A.M., J. Hegde, Sørensen, A.J. [2016].
A 3D Dynamic Voronoi Diagram-Based Path-Planning System for UUVs.

- Application of path-planning/replanning system for underwater vehicles

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Approach

Propose a path-planning/replanning algorithm which could:

- Be implemented in UUVs performing permanent IMR operations;
- Given two points of the susbea factory, connect them with a safe, flyable path;
- Produce fast, safe, path alternatives if an unexpected obstacle is met.

TOOLS

- Voronoi diagram
- Dubins path
- Safety navigation rules

HYP/CONSTRAINTS

- 3D environment
- The map is known
- Moving obstacles are unknown a-priori
- Maximum turning rate for the vehicle

OBJECTIVES

- Simple, intuitive path
- Flyable paths
- Safety concerning distance with known, fixed obstacles
- Safety concerning collision with moving obstacle
- Fast replanning

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Procedure

The general approach of Tsourdos et al. (2011) is utilized:

$$\boldsymbol{P}_s(x_s, y_s) \xrightarrow{\;C_{safe}\;C_{\kappa}\;C_{length}\;,\boldsymbol{r}(q)\;} \boldsymbol{P}_f(x_f, y_f)$$

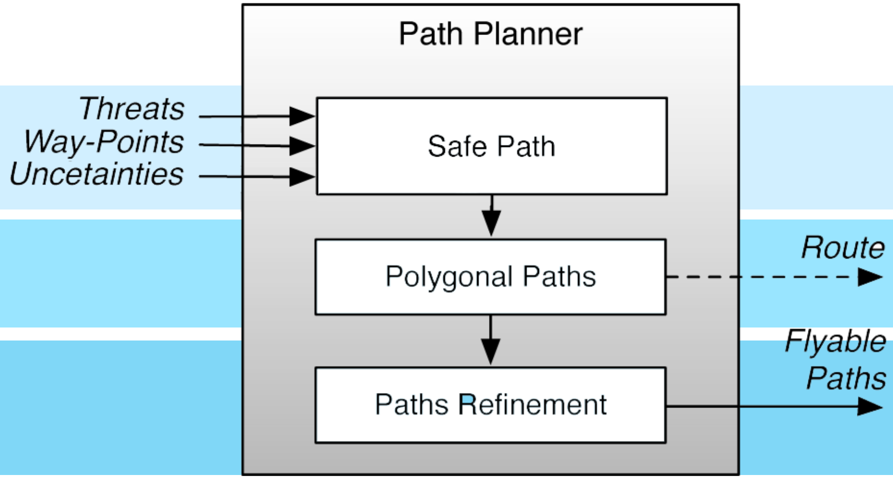
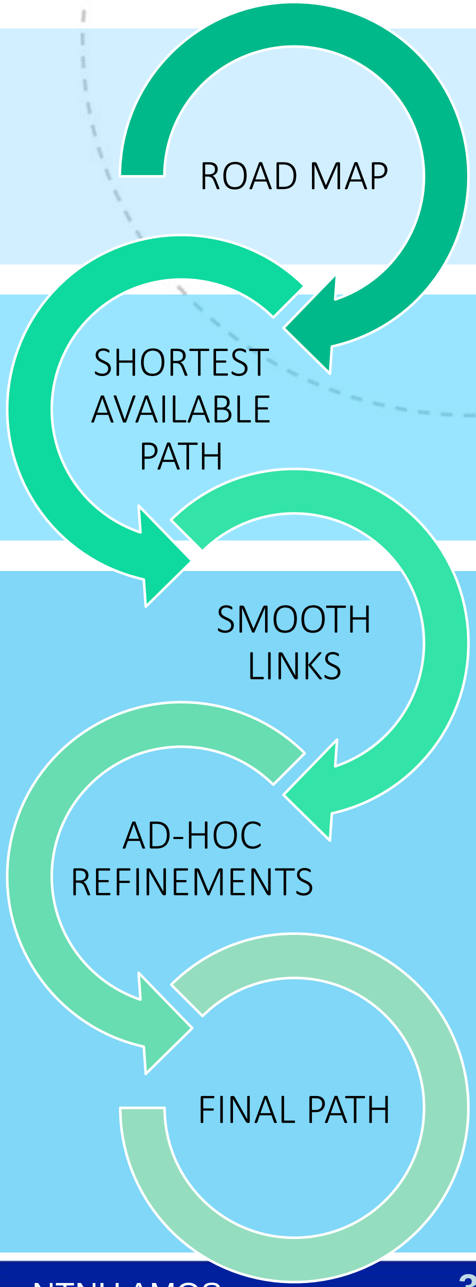
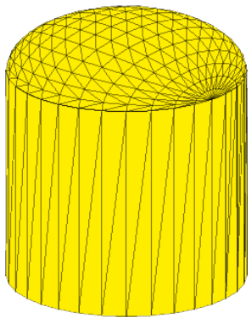


Image from Tsourdos et al. (2011)



Defining Obstacles

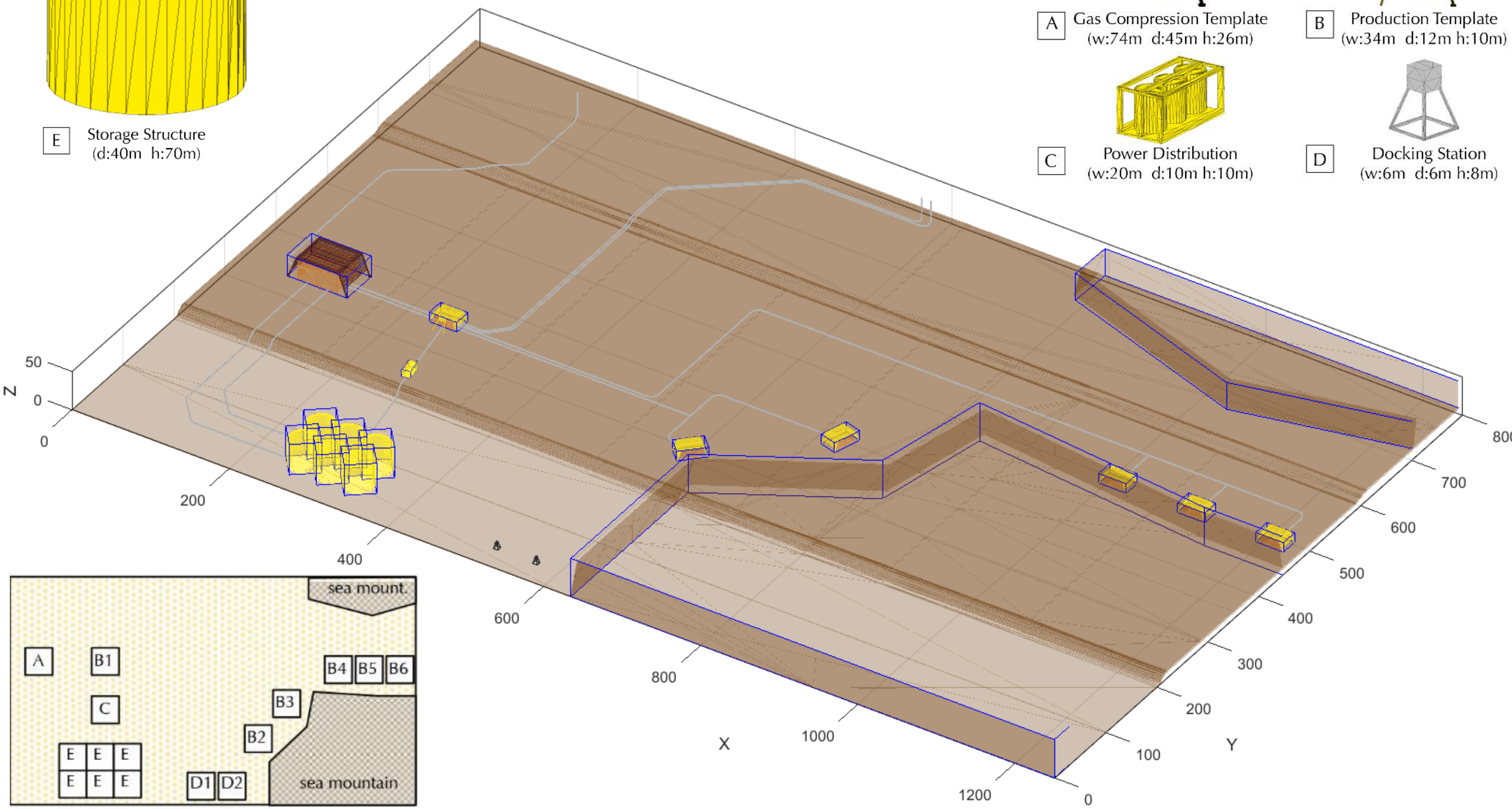
- Obstacles designed in Rhino with realistic specs
- Imported in Matlab and defined the convex hull
- Vertexes are the Voronoi diagram generator points



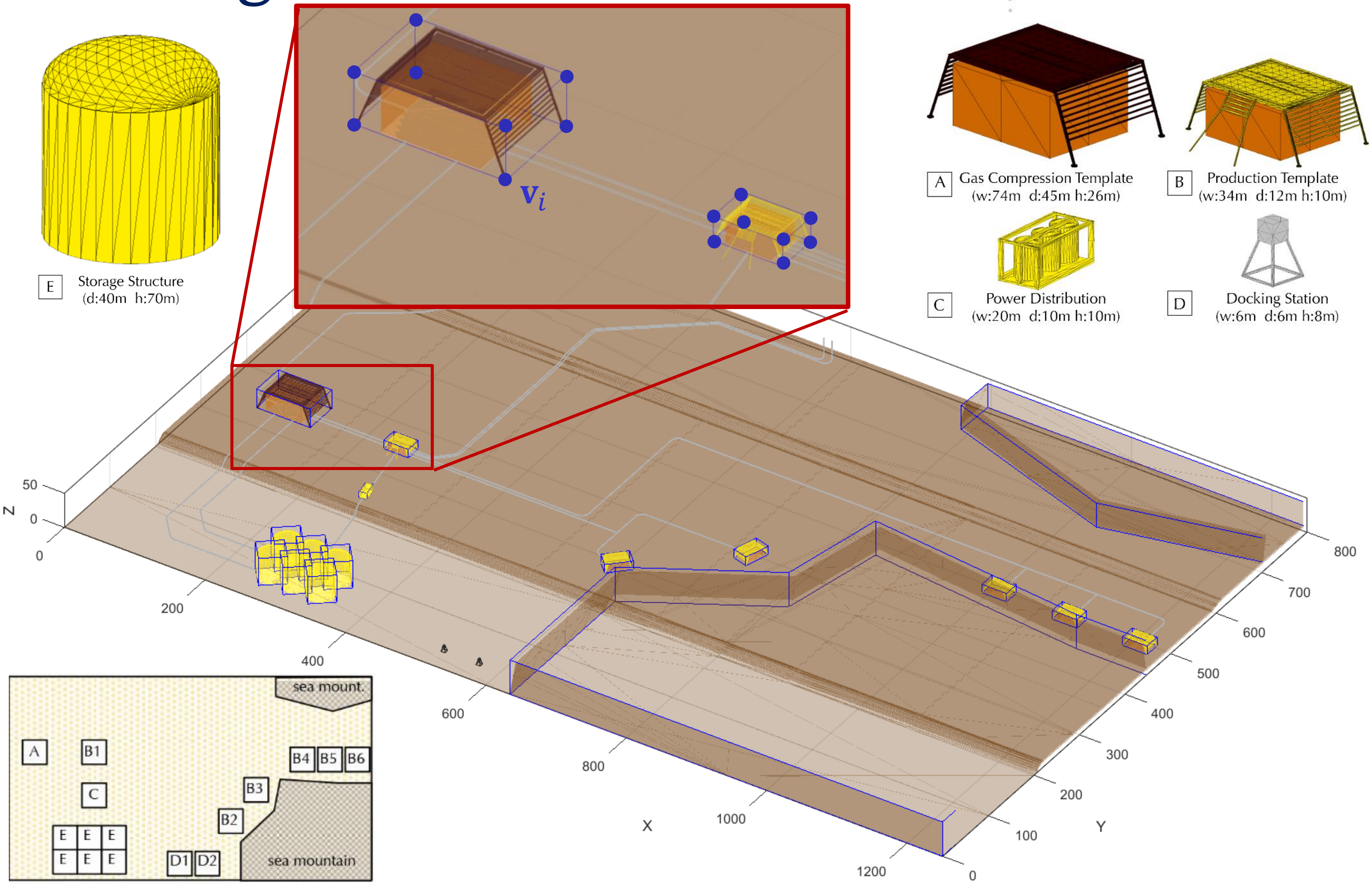
E Storage Structure (d:40m h:70m)

A Gas Compression Template (w:74m d:45m h:26m)

B Production Template (w:34m d:12m h:10m)

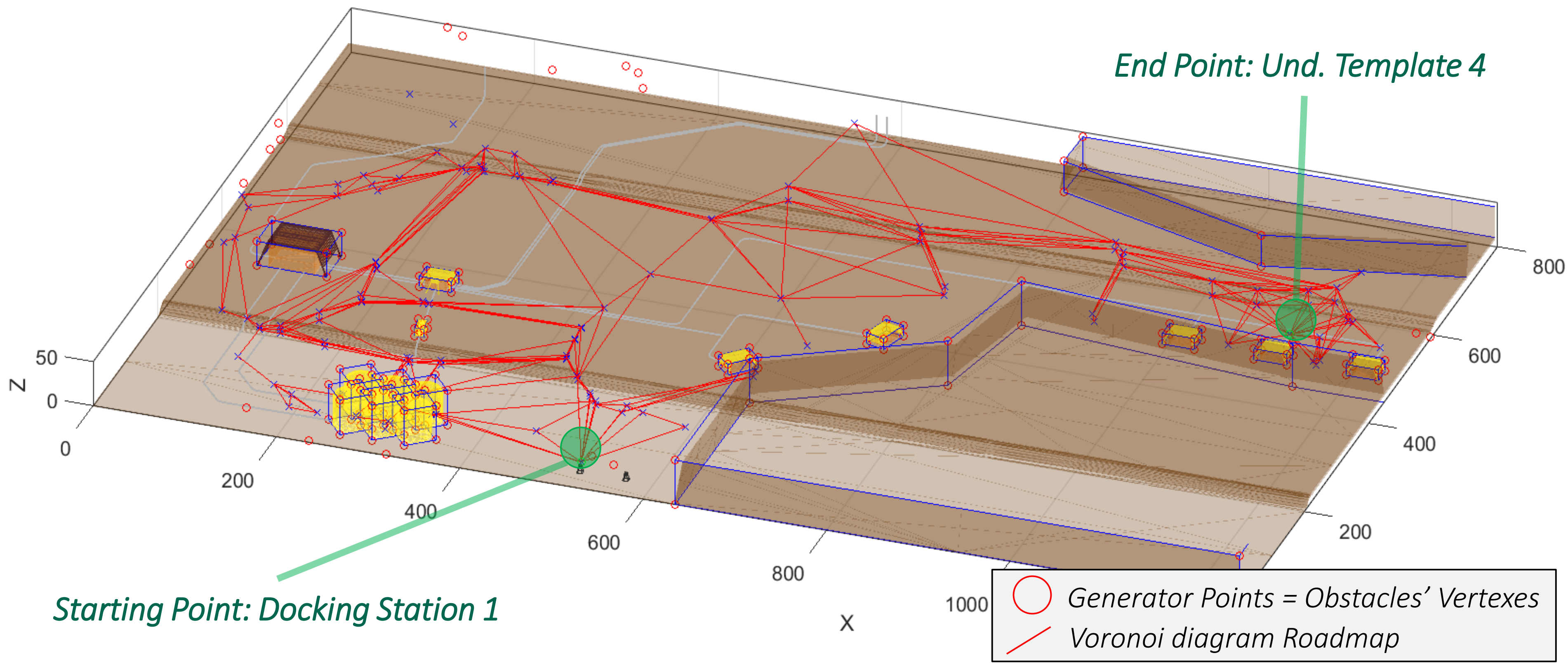


Defining Obstacles



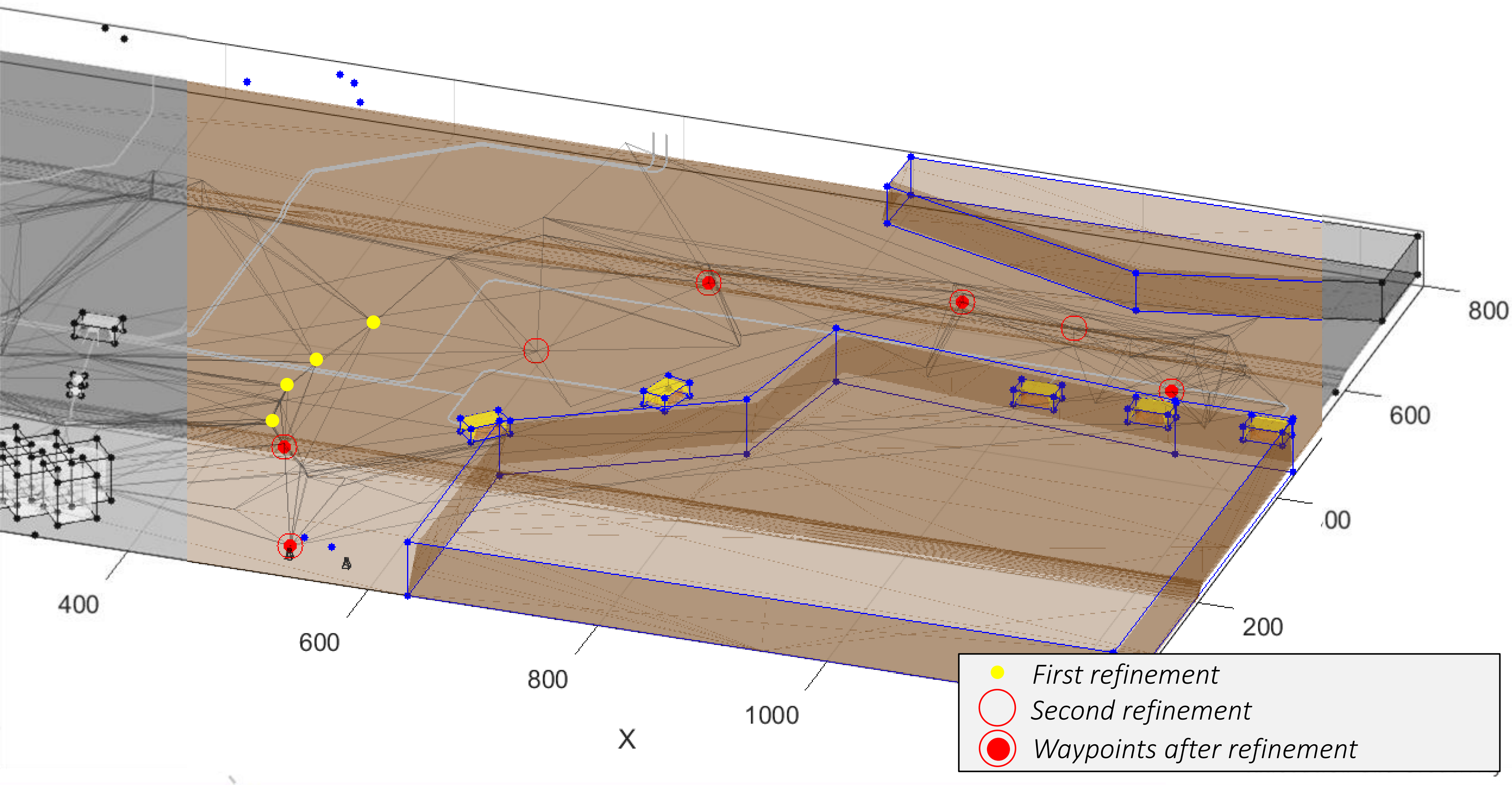
Defining a Road Map

- Red dots are the generator points of the Voronoi diagram;
- Random generator points are created on the edges of the SPS, to constraint the Voronoi diagram;
- Red lines are the Voronoi edges;
- Starting and Final points are defined and connected to the closes vertexes of the roadmap.

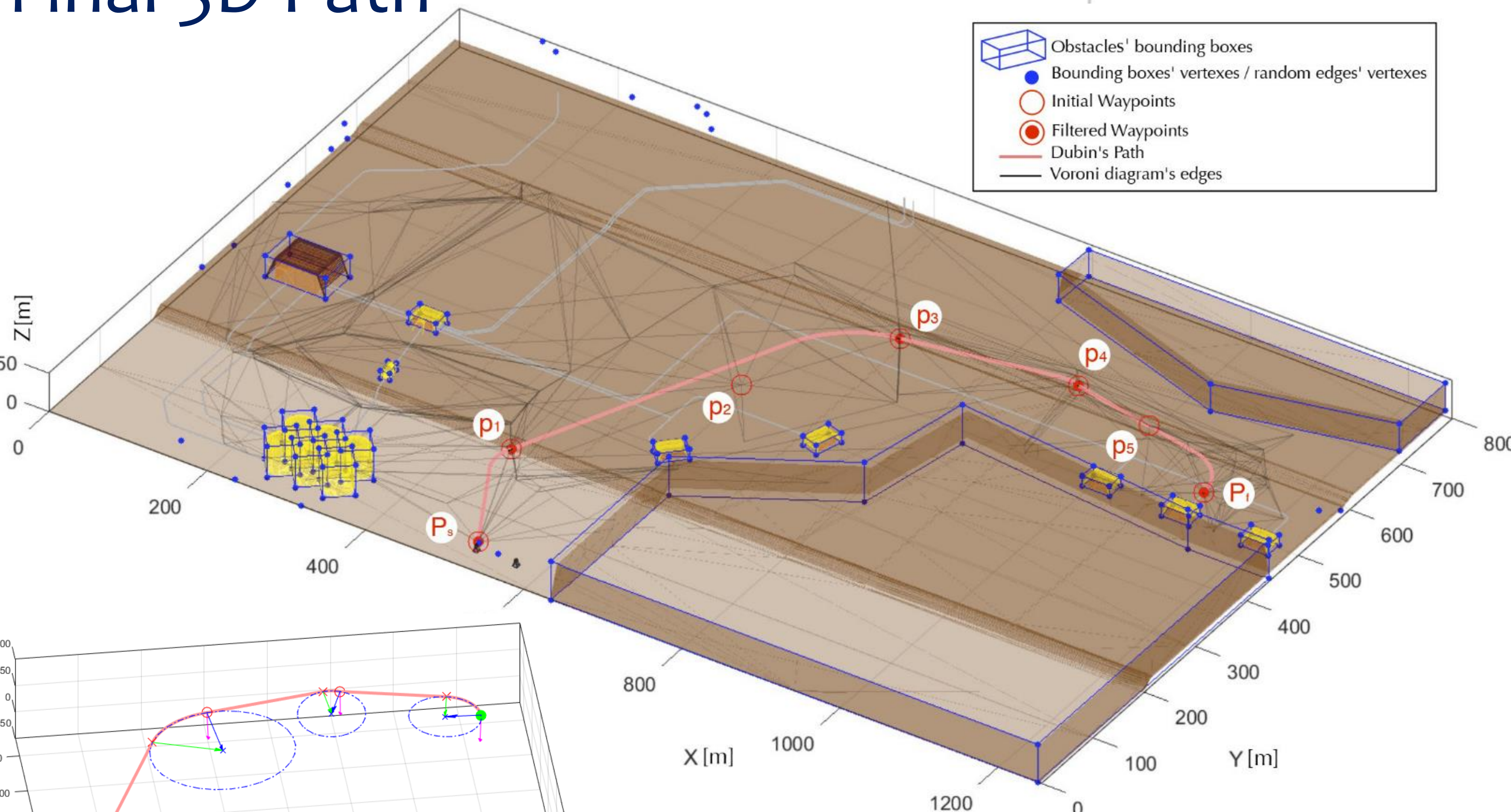


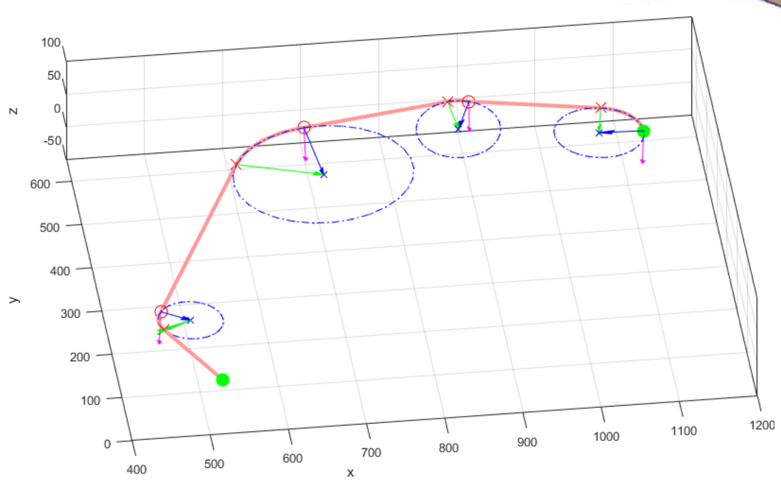
Shortest Path

- Dijkstra Algorithm (with Yan modification) allows to find the nth-shortest path;
- Clearance constraints (minimum distance to the obstacles) must be calculated and checked;
- Further simplifications on the path are done IF the clearance to obstacles does not decrease.



Final 3D Path





- 3D Dubins path are used to smoothen the polygonal path

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Traffic Rules

In order to resolve possible collisions, specific rules have been developed both for surface vessels, and for aerial vehicles.

COLREGS

These rules help the commander's decision process during overtaking, head-on, crossing, and give way scenarios between two vessels, and actions to be taken by a stand-on vessel.

International Maritime Organization, 2005. International Regulations for Preventing Collisions at Sea, 1972.

TCAS

Pertain to the collision avoidance of aerial vehicles. They are utilized to provide vertical separation and resolution advisories also for commercial aircrafts.

US Department of Transportation and Federal Aviation Administration, 2011. Introduction to TCAS II - Version 7.1.

Traffic Rules

No official "traffic rules" are available, yet, for UUVs. But it can be foreseen that a systematic way of resolving conflicting trajectories situations will need to be introduced in the case of more vehicles operating in a confined area.

The idea of COLREG and TCAS have been merged to create simple rules to be followed in case of possible collision. They consider:

- Moving / Static Obstacles;
- Obstacles moving in opposite / same directions of considered vehicles;
- Obstacles crossing left / right;
- Obstacles in same / lower / higher altitude.

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UUVs Traffic Rules

Static obstacles rules:

Obstacle position in horiz. plane (wrt UUV)	Obstacle position in vertical plane (wrt UUV)	Safe navigation rules
Front Left	Lower altitude	Turn right, climb.
Front Left	Same altitude	Turn right, climb.
Front	Lower altitude	Turn right, climb.
Front	Same altitude	Turn right, climb.
Front Right	Lower altitude	Turn left, climb.
Front Right	Same altitude	Turn left, climb.

Moving obstacles rules:

Direction of movement	Obstacle position in horizontal plane (wrt UUV)	Obstacle position in vertical plane (wrt UUV)	Safe navigation rules
Obstacle moving in opposite direction of UUV	Crossing Left	Higher altitude	UUV descends, obstacle climbs.
	Crossing Left	Same altitude	UUV Climbs, obstacle descends.
	Crossing Left	Lower Altitude	UUV Climbs, obstacle descends.
	Crossing Right	Higher altitude	UUV descends, obstacle climbs.
	Crossing Right	**Same altitude**	**UUV Climbs, obstacle descends**.
	Crossing Right	Lower Altitude	UUV Climbs, obstacle descend.
Obstacle moving in same direction as UUV	Crossing Left	Higher altitude	UUV descends, obstacle climbs.
	Crossing Left	Same altitude	UUV descends, obstacle climbs.
	Crossing Left	Lower Altitude	UUV descends, obstacle climbs.
	Crossing Right	Higher altitude	UUV descends, obstacle climbs.
	Crossing Right	Same altitude	UUV descends, obstacle climbs.
	Crossing Right	Lower Altitude	UUV Climbs, obstacle descends.

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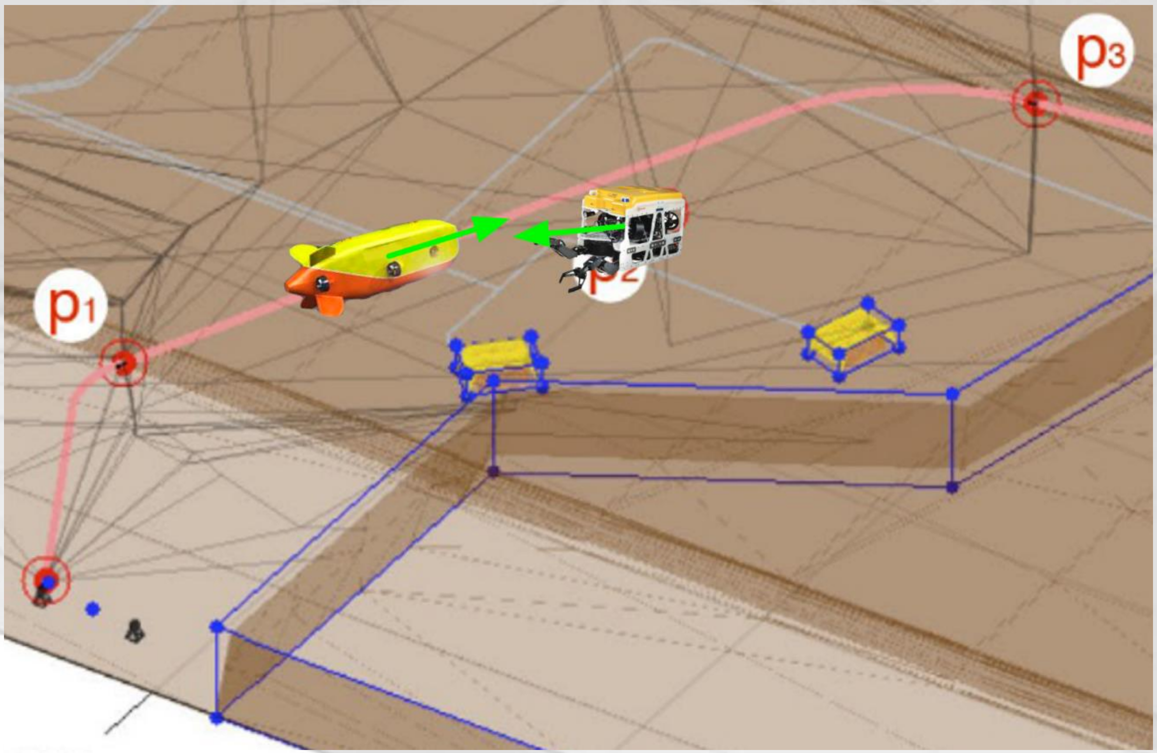
Replanning: hints



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Replanning: hints

- The navigation rules are added as an extra obstacle in the replanning area

Direction of movement	Obstacle position in horizontal plane (wrt UUV)	Obstacle position in vertical plane (wrt UUV)	Safe navigation rules
Obstacle moving in opposite direction of UUV	Crossing Left	Higher altitude	UUV descends, obstacle climbs.
	Crossing Left	Same altitude	UUV Climbs, obstacle descends.
	Crossing Left	Lower Altitude	UUV Climbs, obstacle descends.
	Crossing Right	Higher altitude	UUV descends, obstacle climbs.
	Crossing Right	**Same altitude**	**UUV Climbs, obstacle descends.**
	Crossing Right	Lower Altitude	UUV Climbs, obstacle descend.
Obstacle moving in same direction as UUV	Crossing Left	Higher altitude	UUV descends, obstacle climbs.
	Crossing Left	Same altitude	UUV descends, obstacle climbs.
	Crossing Left	Lower Altitude	UUV descends, obstacle climbs.
	Crossing Right	Higher altitude	UUV descends, obstacle climbs.
	Crossing Right	Same altitude	UUV descends, obstacle climbs.
	Crossing Right	Lower Altitude	UUV Climbs, obstacle descends.

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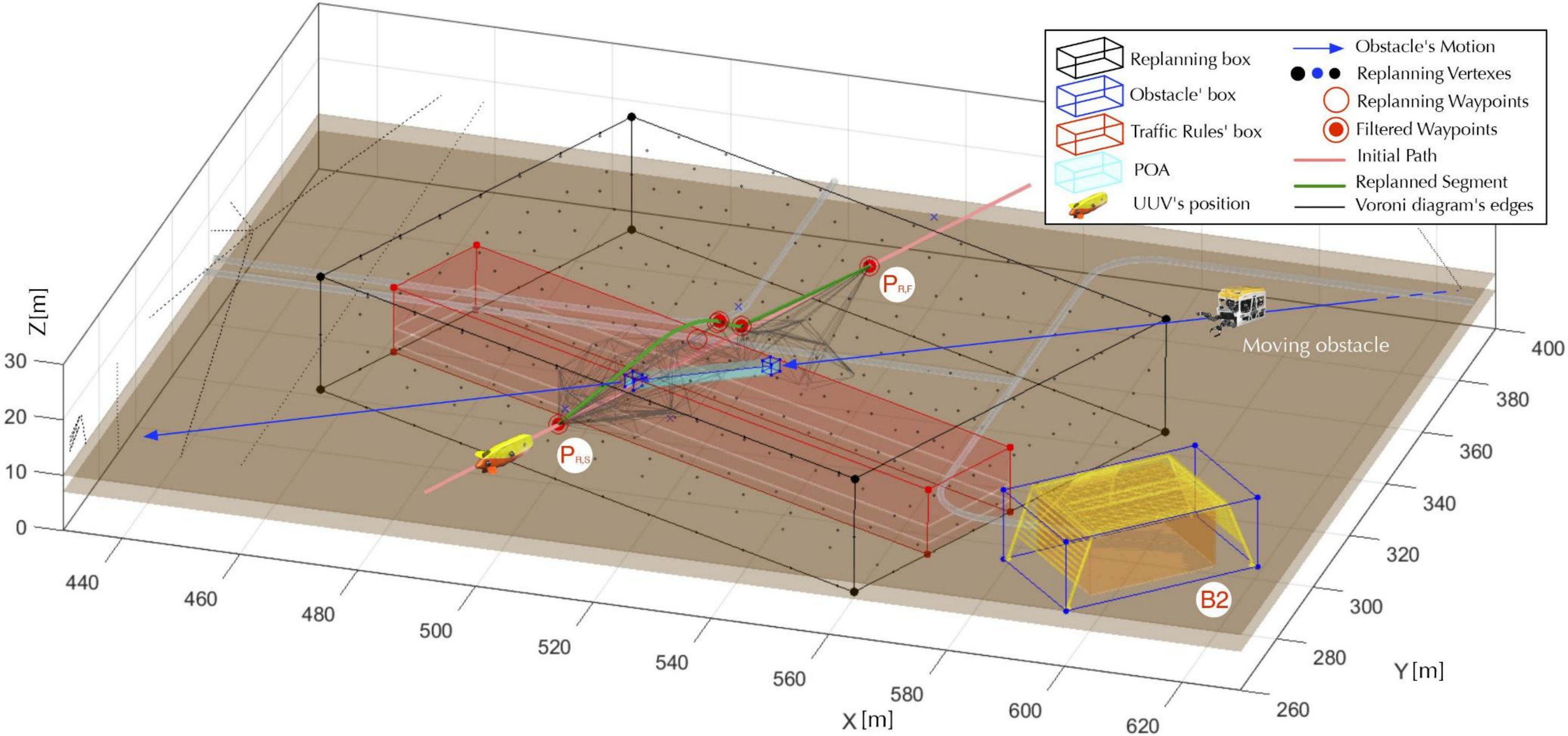
Final Replanned deviation

Replanning Time constantly < 2s



Conclusions and Further Work

- Preliminary results on a HMD system for feedback control of an ROV have been obtained using basic guidance and control algorithms.
- A novel 3D dynamic path-planning/replanning system for UUVs has been proposed, targeting underwater vehicles with extended autonomy characteristics.
  A new set of traffic rules for underwater vehicles has been proposed.
- Perform tests on a large number of operators: easier/more efficient with joystick or HMD? What is faster to learn?
- New "ad hoc" guidance methods
- Include a guidance system and an obstacle detection method, as it has been done for the 2D case
- Full-scale testing

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Innovation and Creativity


Thank you for your attention.