THEME [ICT-2009.2.1]
[Cognitive Systems and Robotics]

Grant agreement for: Collaborative project*

Annex I - "Description of Work"

Project acronym: NOPTILUS

Project full title: " autoNomous, self-Learning, OPTImal and compLete Underwater Systems "

Grant agreement no: 270180

Version date:

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Part A

Workplan Tables

A1:
Project summary

Project Number [1]	270180	Project Acronym [2]	NOPTILUS

One form per project

General information			
Project title [3]	autoNomous, self-Learning, OPTImal and compLete Underwater Systems		
Starting date [4]	01/04/2011		
Duration in months [5]	48		
Call (part) identifier [6]	FP7-ICT-2009-6		
Activity code(s) most relevant to your topic [7]	ICT-2009.2.1: Cognitive Systems and Robotics		
Free keywords [8]			

Abstract [9]

Current multi-AUV systems are far from being capable of fully autonomously taking over real-life complex situation-awareness operations. As such operations require advanced reasoning and decision-making abilities the current designs have to heavily rely on human operators. The involvement of humans, however, is by no means a guarantee of performance; humans can easily be overwhelmed by the information overload, fatigue can act detrimentally to their performance, properly coordinating vehicles actions is hard, and continuous operation is all but impossible. Within NOPTILUS we take the view that an effective fully-autonomous multi-AUV concept/system, is capable of overcoming these shortcomings, by replacing human-operated operations by a fully autonomous one. To successfully attain such an objective, significant advances are required, involving cooperative & cognitive-based communications and sonars (low level), Gaussian Process-based estimation as well as perceptual sensory-motor and learning motion control (medium level), and learning/cognitive-based situation understanding and motion strategies (high level).Of paramount importance is the integration of all these advances and the demonstration of the NOPTILUS system in a realistic environment at the Port of Leixões, utilizing a team of 6 AUVs that will be operating continuously on a 24hours/7days-a-week basis.
As part of this demonstration another important aspect of the NOPTILUS system that of (near-) optimality will be shown. Evaluation of the performance of the overall NOPTILUS system will be performed with emphasis on its robustness, dependability, adaptability and flexibility especially when it deals with completely unknown underwater environments and situations never taught before as well as its ability to provide with arbitrarily-close-to-the-optimal performance.

A2:
List of Beneficiaries

Project Number [1]	270180	Project Acronym [2]	NOPTILUS

List of Beneficiaries

No	Name	Short name	Country	Project entry month[10]	Project exit month
1	CENTRE FOR RESEARCH AND TECHNOLOGY HELLAS	CERTH	Greece	1	48
2	UNIVERSIDADE DO PORTO	FEUP	Portugal	1	48
3	EIDGENOESSISCHE TECHNISCHE HOCHSCHULE ZURICH	ETH Zurich	Switzerland	1	18
4	TECHNISCHE UNIVERSITEIT DELFT	TU Delft	Netherlands	1	48
5	TELECOMMUNICATION SYSTEMS INSTITUTE	TSI	Greece	1	48
6	IMPERIAL COLLEGE OF SCIENCE, TECHNOLOGY AND MEDICINE	Imperial	United Kingdom	1	48
7	OCEANSCAN - MARINE SYSTEMS & TECHNOLOGY LDA	MST	Portugal	1	48
8	APDL - ADMINISTRACAO DOS PORTOS DODOURO E LEIXOES SA	APDL	Portugal	1	48
9	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE	CNRS	France	19	48

A3:
Budget Breakdown

Project Number [1]	270180	Project Acronym [2]	NOPTILUS

One Form per Project

Participant number in this project [11]	Participant short name	Fund. % [12]	Ind. costs [13]	Estimated eligible costs (whole duration of the project)					Requested EU contribution
				RTD / Innovation (A)	Demonstration (B)	Management (C)	Other (D)	Total A+B+C+D	
1	CERTH	75.0	S	887,487.00	0.00	51,345.00	0.00	938,832.00	716,960.00
2	FEUP	75.0	T	838,680.00	0.00	79,900.00	0.00	918,580.00	708,910.00
3 (TERMINATED)	ETH Zurich	75.0	T	146,622.00	0.00	0.00	0.00	146,622.00	109,966.00
4	TU Delft	75.0	A	307,639.00	0.00	63,185.00	0.00	370,824.00	293,914.00
5	TSI	75.0	T	587,520.00	0.00	71,900.00	0.00	659,420.00	512,540.00
6	Imperial	75.0	T	526,483.00	0.00	2,500.00	50,004.00	578,987.00	447,366.00
7	MST	75.0	T	512,691.00	0.00	61,676.00	0.00	574,367.00	446,194.00
8	APDL	50.0	F	399,660.00	0.00	46,380.00	0.00	446,040.00	246,210.00
9	CNRS	75.0	T	276,636.00	0.00	90,174.00	0.00	366,810.00	297,651.00
Total				4,483,418.00	0.00	467,060.00	50,004.00	5,000,482.00	3,779,711.00

Note that the budget mentioned in this table is the total budget requested by the Beneficiary and associated Third Parties.

*** The following funding schemes are distinguished**

Collaborative Project (if a distinction is made in the call please state which type of Collaborative project is referred to: (i) Small of medium-scale focused research project, (ii) Large-scale integrating project, (iii) Project targeted to special groups such as SMEs and other smaller actors), Network of Excellence, Coordination Action, Support Action.

1. Project number

The project number has been assigned by the Commission as the unique identifier for your project, and it cannot be changed. The project number **should appear on each page of the grant agreement preparation documents** to prevent errors during its handling.

2. Project acronym

Use the project acronym as indicated in the submitted proposal. It cannot be changed, unless agreed during the negotiations. The same acronym **should appear on each page of the grant agreement preparation documents** to prevent errors during its handling.

3. Project title

Use the title (preferably no longer than 200 characters) as indicated in the submitted proposal. Minor corrections are possible if agreed during the preparation of the grant agreement.

4. Starting date

Unless a specific (fixed) starting date is duly justified and agreed upon during the preparation of the Grant Agreement, the project will start on the first day of the month following the entry info force of the Grant Agreement (NB : entry into force = signature by the Commission). Please note that if a fixed starting date is used, you will be required to provide a detailed justification on a separate note.

5. Duration

Insert the duration of the project in full months.

6. Call (part) identifier

The Call (part) identifier is the reference number given in the call or part of the call you were addressing, as indicated in the publication of the call in the Official Journal of the European Union. You have to use the identifier given by the Commission in the letter inviting to prepare the grant agreement.

7. Activity code

Select the activity code from the drop-down menu.

8. Free keywords

Use the free keywords from your original proposal; changes and additions are possible.

9. Abstract

10. The month at which the participant joined the consortium, month 1 marking the start date of the project, and all other start dates being relative to this start date.

11. The number allocated by the Consortium to the participant for this project.

12. Include the funding % for RTD/Innovation – either 50% or 75%

13. Indirect cost model
- **A: Actual Costs**
- **S: Actual Costs Simplified Method**
- **T: Transitional Flat rate**
- **F :Flat Rate**

Workplan Tables

Project number

270180

Project title

NOPTILUS—autoNomous, self-Learning, OPTImal and compLete Underwater Systems

Call (part) identifier

FP7-ICT-2009-6

Funding scheme

Collaborative project

WT1
List of work packages

Project Number [1]	270180	Project Acronym [2]	NOPTILUS

LIST OF WORK PACKAGES (WP)

WP Number [53]	WP Title	Type of activity [54]	Lead beneficiary number [55]	Person-months [56]	Start month [57]	End month [58]
WP 1	Project Management	MGT	1	19.00	1	48
WP 2	System Components	RTD	2	75.00	1	36
WP 3	Communications, Sensing and Localization	RTD	5	76.00	1	30
WP 4	Cooperative Distributed Estimation	RTD	1	66.00	7	30
WP 5	Motion and Sensory-Motor Control	RTD	3	52.30	7	30
WP 6	Situation Understanding	RTD	5	41.00	7	42
WP 7	Optimal Planning, Assignment and Navigation	RTD	5	68.00	7	42
WP 8	System Integration and Evaluation	RTD	7	167.00	1	48
WP 9	Dissemination, Training and Exploitation	MGT	2	32.00	1	48
			Total	596.30		

WT2:
List of Deliverables

Project Number [1]	270180	Project Acronym [2]	NOPTILUS

List of Deliverables - to be submitted for review to EC

Deliverable Number [61]	Deliverable Title	WP number [53]	Lead beneficiary number	Estimated indicative person-months	Nature [62]	Dissemination level [63]	Delivery date [64]
D1.1	Project Management Plan	1	1	5.00	R	CO	1
D1.2	Final Report	1	1	14.00	R	RE	48
D2.1	System Specification	2	7	8.00	R	CO	6
D2.2	Integrated multi-AUV system	2	2	67.00	P	CO	36
D3.1	Synergetic/ Cognitive Sonar AUV Communications	3	4	15.00	R	PU	15
D3.2	Photometric stereo through a strongly scattering medium	3	6	22.00	R	PU	22
D3.3	Cooperative AUV Localization	3	5	12.00	R	PU	12
D3.4	Collaborative Underwater Sensing	3	5	14.00	R	PU	14
D3.5	Surface estimation with photometric stereo and sonar	3	6	13.00	R	PU	13
D4.1	Cooperative AUV Static and Dynamic Mapping Construction	4	1	33.00	R	PU	30
D4.2	Cooperative AUV Dynamic Process Tracking	4	1	33.00	R	PU	30
D5.1	Cooperative AUV Motion Control	5	1	11.90	R	PU	30
D5.2	AUV Sensory-motor control	5	3	30.40	R	PU	30

Delive-rable Number [61]	Deliverable Title	WP number [53]	Lead benefi-ciary number	Estimated indicative person-months	Nature [62]	Dissemi-nation level [63]	Delivery date [64]
D5.3	Switching Motion/Sensory-motor control	5	3	10.00	R	PU	30
D6.1	Learning from Past Missions Design for multi-AUV Situation Understanding	6	5	18.00	R	PU	36
D6.2	Structured Prediction for multi-AUV Situation Understanding	6	5	14.00	R	PU	36
D6.3	Combining Learning from Past Missions and Structured Prediction Designs for multi-AUV Situation Understanding	6	5	9.00	R	PU	42
D7.1	The NOPTILUS Planning, Assignment and Navigation Module (PAN with CAO algorithm)	7	1	37.00	R	PU	36
D7.2	The NOPTILUS Planning, Assignment and Navigation Module (incorporating underwater constraints and integrating with the Situation Understanding Module)	7	1	20.00	R	PU	42
D7.3	The overall NOPTILUS software system	7	1	11.00	R	PU	42
D8.1	Evaluation Methodology and Definition of Accuracy/	8	7	10.00	R	PU	12

Delive-rable Number [61]	Deliverable Title	WP number [53]	Lead benefi-ciary number	Estimated indicative person-months	Nature [62]	Dissemi-nation level [63]	Delivery date [64]
	Efficiency Targets						
D8.2	Fixed components	8	7	10.00	R	RE	24
D8.3	AUV System	8	7	20.00	R	RE	36
D8.4	ASV System	8	7	13.00	R	RE	30
D8.5	NOPTILUS System (hardware and software)	8	7	41.00	R	RE	42
D8.6	Demonstration and evaluation report	8	2	73.00	R	PU	48
D9.1	NOPTILUS Website, Video, CD-ROM and project-leaflet	9	2	2.00	O	PU	3
D9.2.1	Dissemination and Use of Foreground (1st version)	9	2	2.00	R	PP	6
D9.2.2	Dissemination and Use of Foreground (2nd version)	9	2	9.00	R	PP	48
D9.3	Open-House Fairs at NOPTILUS Test Case	9	2	4.00	O	PU	48
D9.4	Scientific Publications, Summer Schools, Training Material, Organization of Conferences, Workshops and Technology Transfer Meetings	9	2	15.00	O	PU	48
			Total	596.30			

WT3:
Work package description

Project Number [1]	270180	Project Acronym [2]	NOPTILUS

One form per Work Package

Work package number [53]	WP1	Type of activity [54]	MGT
Work package title	Project Management		
Start month	1		
End month	48		
Lead beneficiary number [55]	1		

Objectives

The aim of this work package is the management and co-ordination of the whole project in order to achieve the contractual obligations and expected results. More specifically, the particular objectives are:
- to guarantee the successful completion of the project within the agreed time, cost and quality;
- to ensure an overall consistency of the work to be carried out;
- to track the progress of milestones and deliverables against the project schedule;
- to support all work package leaders in the planning and implementation of individual work packages;
- to ensure compliance with the EC standard and procedures for the project management and tracking;
- to assure an effective communication among the consortium partners;
- to provide a direct contact for the relevant Commission services for all communication and reporting;
- to ensure that full advantage is taken of the opportunities to disseminate the project results

Description of work and role of partners

CERTH will coordinate the project and will be responsible for ensuring that the correct procedures are applied and deadlines and obligations are met. Appropriate management processes will be implemented according to the ISO 10006 project management standard. The first 3 months will be strategic for implementing the whole project management structure. CERTH will lead WP1 with the assistance of the other WP Leaders (Management Board). WP1 is directly linked to all other project components since it includes overall coordination of the different project work packages and provides publicity for the project as a whole as well as for separate work packages.
WP1 is subdivided in the following tasks:
Task 1.1. Strategic Management
This task will cover the following activities:
- Elaborate a Project Management Plan that provides the main decision-making rules and the main procedures regarding the smooth functioning of the project (CERTH).
- Define performance measurement baselines (all).
- Compare the project progress to the planned schedule and take any corrective action if necessary (CERTH).
- Identify the risk management baselines (CERTH).
- Ensure that milestones are met and deliverables produced are of high quality (CERTH).
- Organize the information flow throughout the project between all participants (CERTH).
- Coordinate the NOPTILUS Management Board (CERTH).
- Coordinate the project reviews (CERTH).
- Produce strategic documents (e.g. major changes in the project) for the Steering Committee (CERTH).
- Coordinate the interactions with the EU (CERTH).
Task 1.2 Technical Management
The work to be carried within task 1.2 is related to both management levels: Integrative management and WP management. Integrative management activities are related to the advancement of the project, including the organization of meetings needed for proper project monitoring and production of deliverables. At the level of WP, WP Leaders will be responsible for the progress and for the deliverables. They will monitor the technical management of the WP by performing the following activities:
- Management of project integration. This process contains the project management plan, the management of interfaces, the analysis of advancement and the conclusion of the project (CERTH).

- Management of the content. It comprises the conception and definition of the content, the definition of research activities and the control of evolutions (all).
- Technical coordination of tasks execution (all).
- Supervision of preparation of reports, cost statements, publications (CERTH).
- Keeping an effective communication with other WPs (all).
- Identification and resolution of potential conflicts, linked for instance to knowledge access rights (all).
- Organization of internal technical meetings (all).
- Organization of the Steering and Advisory Committee meetings (CERTH).

Task 1.3 Administrative and Contractual Management

The work to be carried within task 1.3 is related to integrative management level and consists of setting up the management processes needed to perform the following activities:
- Process cost estimates, define coherent schedules and assign responsibilities (CERTH).
- Control manpower consumption with respect to the reports submitted by beneficiaries (CERTH).
- Management of delay in relation to activities, duration estimation, planning, and delay management (CERTH).
- Management of costs comprising cost estimation, budget, and actual cost (CERTH).
- Management of resources including planning, assignment, and control processes (CERTH).
- Management of communication including communication plan, organisation, and control of interfaces (CERTH).
- Management of purchases including the planning and control of purchases (CERTH).
- Management of risks with identification, evaluation and control of risks (CERTH).
- Management of legal aspects for the consortium agreement and beneficiary contracts (CERTH).

Task 1.3 also includes the periodic update of the project documents related to the different processes (progress reports, work-plan, cost statements, communication reports) and the supervision of the preparation of the deliverables and technical reports from the different WPs.

Person-Months per Participant

Participant number [10]	Participant short name [11]	Person-months per participant
1	CERTH	1.00
2	FEUP	4.00
3	ETH Zurich	0.00
4	TU Delft	2.00
5	TSI	2.00
6	Imperial	0.00
7	MST	4.00
8	APDL	2.00
9	CNRS	4.00
	Total	19.00

List of deliverables

Deliverable Number [61]	Deliverable Title	Lead beneficiary number	Estimated indicative person-months	Nature [62]	Dissemination level [63]	Delivery date [64]
D1.1	Project Management Plan	1	5.00	R	CO	1
D1.2	Final Report	1	14.00	R	RE	48
		Total	19.00			

Description of deliverables

D1.1) Project Management Plan: It will provide the main decision-making rules and the main procedures regarding the smooth functioning of the project. [month 1]

D1.2) Final Report: It will describe the achievements of the project as well as its progress and financial status. It will also describe the main dissemination activities undertaken during the NOPTILUS project and include the final plan for the dissemination and use of foreground. [month 48]

Schedule of relevant Milestones

Milestone number [59]	Milestone name	Lead beneficiary number	Delivery date from Annex I [60]	Comments

WT3:
Work package description

Project Number [1]	270180	Project Acronym [2]	NOPTILUS

One form per Work Package

Work package number [53]	WP2	Type of activity [54]	RTD
Work package title	System Components		
Start month	1		
End month	36		
Lead beneficiary number [55]	2		

Objectives

The aim of this work package is
- the definition of all hardware, software and interfacing components, necessary for the operation of the NOPTILUS system;
- the definition of all additional hardware, software and interfacing components, necessary for the operation of the NOPTILUS system within a general-purpose application like the NOPTILUS test case harbour application.
- the development of all interfacing components;
- the installation and verification of all system components.
Description of work and role of partners

Description of work and role of partners

FEUP will lead WP2 in close cooperation with the other partners: APDL will provide the end-user requirements for the six types of operations and the facilities for testing and evaluation, as well as feedback on the developments; MST and FEUP will address the definition, development, installation and verification of all system components with the assistance of the other partners; the remaining partners will provide the technical specifications for the installation of the additional hardware and software on the AUVs, ASVs, ROVs and gateway buoys provided by FEUP and MST.
WP2 is subdivided in the following tasks:
Task 2.1. System Specification
The work to be carried within task 2.1 concerns the specification of the system where the components of NOPTILUS will be mounted, integrated and tested and then finally integrated for the operation of the NOPTILUS system. This will be done in accordance to the IEEE Standard 1220-2005 for the systems engineering process.
Task 2.2. Gateway buoys and moored sensors
Task 2.2 concerns the adaptation of gateway buoys and moored sensors from FEUP to the specifications defined in task 2.1. This entails:
- To develop electric and computer interfaces to new acoustic modems and to other sensors.
- To deploy the buoys and sensors at selected locations.
- To interface the system to the Internet for remote access.
Task 2.3. Command centre
Task 2.3 concerns tailoring the Neptus command and control framework from FEUP to the specifications of the project and to install it on a command centre, consisting of computer network to be installed at APDL. Operations and tests will be run from this command centre.
Task 2.4. AUV/ROV hardware and software upgrades
Task 2.4 concerns the upgrades of AUV/ROV hardware and software according the specification defined in task 2.1. This entails:
- To develop mechanical, electric and computer interfaces to the sensors and acoustic modems that will be mounted for testing and evaluation.
- To install a separate computer system to run the software applications developed by the other partners.
- To provide a simulation environment for remote testing and evaluation.
Task 2.5. ASV hardware and software upgrades
Task 2.5 concerns the upgrades of ASV hardware and software according the specification defined in task 2.1. This entails:
- To develop mechanical, electric and computer interfaces to the sensors and acoustic modems that will be

mounted for testing and evaluation.
- To install a separate computer system to run the software applications developed by the other partners.
- To provide a simulation environment for remote testing and evaluation.
Task 2.6. Logistic facilities at the harbour
Task 2.6 concerns the development of logistic facilities at APDL to support the integration tests and the demonstrations. This entails developing the setup for automated release of vehicles and for integration with existing systems

Person-Months per Participant

Participant number [10]	Participant short name [11]	Person-months per participant
1	CERTH	1.00
2	FEUP	25.00
3	ETH Zurich	0.00
4	TU Delft	4.00
5	TSI	3.00
6	Imperial	5.00
7	MST	28.00
8	APDL	9.00
9	CNRS	0.00
	Total	75.00

List of deliverables

Delive-rable Number [61]	Deliverable Title	Lead benefi-ciary number	Estimated indicative person-months	Nature [62]	Dissemi-nation level [63]	Delivery date [64]
D2.1	System Specification	7	8.00	R	CO	6
D2.2	Integrated multi-AUV system	2	67.00	P	CO	36
		Total	75.00			

Description of deliverables

D2.1) System Specification: This will provide the specifications of the system where the components of NOPTILUS will be mounted, integrated and tested and for the operation of the NOPTILUS system. [month 6]

D2.2) Integrated multi-AUV system: This consists of a set of (a) two gateway buoys and two bottom-mounted sensors with acoustic modems deployed at APDL; (b) the computer network installed at APDL and running the Neptus command and control framework from FEUP with provisions for remote access;(c) the set of all upgraded underwater vehicles to be used in the project; (d) the upgraded ASV to be used in the project and (e) the logistic facilities at APDL. [month 36]

Schedule of relevant Milestones

Milestone number [59]	Milestone name	Lead beneficiary number	Delivery date from Annex I [60]	Comments
MS1	System Specification Complete	7	6	D2.1 Ready

WT3:
Work package description

Project Number [1]	270180	Project Acronym [2]	NOPTILUS

One form per Work Package

Work package number [53]	WP3	Type of activity [54]	RTD
Work package title	Communications, Sensing and Localization		
Start month	1		
End month	30		
Lead beneficiary number [55]	5		

Objectives

The focus of this work package is to successfully address the low-level NOPTILUS objectives (O3)-(O6) by designing and developing all necessary NOPTILUS modules for
- High-throughput and reliability cooperative (multi-carrier) communication sonar-based system;
- Advanced but low-cost "seeing through murky waters" vision system;
- High-efficiency, distributed, cooperative AUV localization system;
- Collaborative sensing system that employs MIMO/cognitive sonar techniques;
- Fusion of sonar/image measurements and
- Interfacing of sonar, image or fused measurements with the estimation and control systems of WP4 and WP5, respectively.

Description of work and role of partners

WP3 is subdivided in the following tasks:
Task 3.1. Underwater Communications
- Multicarrier modulation systems have the ability to reach high throughputs in an underwater environment, but it is necessary to adapt the system to account for the different Doppler shifts of the different paths of the channel. To address this issue, we will correlate the received signal with different Doppler-shifted versions of the transmitted waveform in order to capture all the energy that is present in the received signal. The resulting correlator outputs will then be efficiently combined to obtain the transmitted information symbols. Note, that this approach requires estimating the amplitudes, time delays, and Doppler shifts of the different paths of the propagation environment, which will be achieved by designing novel pilot sequences.
- The throughput and/or reliability of a multicarrier communication system can be improved by employing a (vertical) hydrophone array. The availability of multiple output channels can also be exploited to tackle the Doppler effects introduced by the underwater channel. Specifically, we will use the diversity of the multiple channels to remove the inter carrier interference in a multicarrier system. Basically, every extra output channel creates a new equation in the same number of unknowns (the transmitted information symbols), and thus there is more redundancy in the system which leads to improved performance and increased reliability
- When different paths are affected by different Doppler shifts, there may exist better transformation-based modulation schemes than multicarrier modulation. For instance, the Mellin transform is known to be a scale-invariant transformation that can transform a linear combination of a set of weighted and scaled versions of a pulse into the Mellin transform of that pulse multiplied with a factor that depends on the weights and scales. However, when the different pulses are also delayed in time, the Mellin transform does not have a particularly interesting form. To address this limitation, we plan to investigate methods for adapting this transformation in order to explicitly consider time delays.
- We will also study a C-MAC layer where the interference will be sensed and the transmission of a multicarrier signal will be adapted accordingly by means of power and bit loading. This is very reminiscent of current work carried out in the field of cognitive radio, where every cognitive radio (consisting of a transmitter and a receiver) opportunistically gains wireless access by claiming resources (e.g., carriers) that are used at that point in space and time. We plan to transfer this cognitive radio principle to the underwater arena, where it will need to be adapted and extended so as to deal with the additional challenges of Doppler spread and latency.
- To further improve the overall throughput of the network, collaborative communication schemes will be developed in combination with the above C-MAC. It is well known that the optimal throughput of the C-MAC layer discussed above (which constitutes a form of Nash equilibrium) can be much lower than what could be achieved

by a central control unit that gathers all the information. Hence, we plan to investigate methods for improving the C-MAC throughput by adding a collaborative element to the system. Possible tools to reach a better throughput are Nash bargaining or interference pricing.
Task 3.2. Underwater Vision
- Modeling the distribution of the shape and size of suspended particles in murky waters in order to model the propagation of the light through the water. Modeling the propagation of light through a strongly scattering medium, with shifts and vibrations of the equipment.
- Developing photometric stereo techniques for "seeing through murky waters", taking into consideration the model of light propagation through water, in real operational conditions. The distribution of the shape and size of the suspended particles in murky waters will be estimated in order to model the propagation of the light in underwater environments. Thus, the state of the art of underwater photometric stereo will be advanced as a more realistic modeling of the scattering process will be developed and used.
- Produce an estimate of the imaged surface from the surface normals, estimated by photometric stereo, with an error estimate for each surface patch.
Task 3.3. Cooperative Underwater Localization
- Develop multipath and path loss (error) models for the underwater acoustic channel. Distance from a beacon/landmark or other AUV is derived from time delay and/or received signal strength measurements. Accurate localization (e.g., by means of Maximum Likelihood refinement) requires appropriate statistical models of multipath and path loss for the underwater acoustic channel. There is very little modeling work to date on related issues, and this is primarily in the context of de-reverberation/equalization.
- Devise methods to fuse distance and motion information for improved localization. Unlike mobile phones or sensors, AUVs are equipped with rather sophisticated motion sensing instruments that provide valuable information. We will investigate ways of fusing distance estimates and motion information to improve localization accuracy and track the location of each AUV in a distributed yet collaborative manner.
- Consider ways of anchoring the solution with minimal GPS readings. A key issue is how to anchor the solution and ensure limited uncertainty when the AUVs are submerged most of the time, and no beacons can be deployed on the surface. One possibility is to have one or more AUVs re-surface when needed to obtain a GPS fix. A single AUV can take multiple GPS readings while it is moving and others are measuring distances to it – thus yielding multiple anchors. The geometry of these measurements is important, as, e.g., three GPS readings on a line cannot disambiguate the three degrees of freedom. We will investigate optimizing the schedule of GPS readings to minimize localization error.
- Devise ways to operate at severely limited communication rates. Work to date on MDS for cooperative localization in wireless sensor networks assumes that i) sensors are static or move very slowly relative to distance acquisition; and ii) there is sufficient bandwidth so that timely and frequent communication between adjacent nodes is possible. Neither of the above holds in our present context. Underwater acoustic communication rates are limited to a few kilobits per second (or even lower) in realistic scenarios, and AUVs may glide at non-negligible speeds relative to wave propagation. These constraints demand serious re-thinking of distributed implementations of MDS, including judicious quantization of the distance estimates.
- Exploit motion to resolve rotational indeterminacy. A very interesting observation that goes back to [L3] is that if one computes distances once, then scales the axes (e.g., contracts all x-coordinates by a certain factor, and all y-coordinates by another factor) and computes distances again, there is a unique solution to the localization problem. This is a remarkable fact that has spawned considerable interest in a field known as three-way analysis. In our present context, it is intriguing to consider exploiting “swarm” motion to generate multiple sets of distances corresponding to different scaling of the x-y-z axes. Even if exact scaling of the axes cannot be accomplished this way, working with a set of distances acquired under motion can lead to an over-determined problem not suffering from rotational ambiguity. This is a very promising research direction to be explored as part of the work to be undertaken in NOPTILUS.
Task 3.4. Collaborative Sensing using Virtual MIMO Sonar
- Devise methods for motion locking between pairs of adjacent AUVs. Relative motion between two AUV mates is an issue, as it implies different Doppler shifts and possibly different multipath channels. This implies that the AUVs in a pair should be motion-locked to within acceptable tolerance. Appropriate mechanisms for achieving this should be devised. Such locking is automatic between neighbors in swarm mode, which suggests that pairing and motion locking can be achieved by mimicking swarm-inducing mechanisms.
- Explore waveform design and synchronization issues. Due to the severe nature of multipath in the underwater acoustic environment, special care should be exercised in designing appropriate orthogonal codes for the different sonars.
A simple option is to use pseudo-random codes, but these require long lengths to ensure quasi-orthogonality. Multicarrier codes are another option that we will explore. Waveform synchronization is

important in both transmit- and receive- ends to reap the MIMO gain.
- Explore ways to migrate and adapt ideas from cognitive radar to cognitive sonar operation. There has been considerable recent interest in cognitive radar [L13], whose key premise is that the transmitter should learn and adapt to the environment it senses – i.e., change its illumination pattern to better explore the search space and narrow-down the targets faster. We envision similar developments in sonar. This is completely uncharted territory in the sonar community as of this writing, and we will devote part of our effort to exploratory research in this direction.
Task 3.5 Sonar/Image Fusion and Interfacing with Control Modules
- Combine ("fuse") the shape information extracted with photometric stereo with sonar information, taking into consideration the uncertainties in each type of information. The shape information extracted with photometric stereo will be combined with sonar information, taking into consideration the uncertainty present in each type of measurements. This is a challenging problem of information fusion, which requires merging two images acquired by two totally different modalities, whose optimal functionality occurs at different ranges. The fusion of these two modalities will allow the vehicle to operate optimally at large, as well as close distances over a wide range of visibility conditions.
- Interfacing with the estimation modules of WP4 and motion and sensory-motion control modules of WP5, by extract albedo information for inspection tasks, while using the extracted shape information for navigation purposes.

Person-Months per Participant

Participant number [10]	Participant short name [11]	Person-months per participant
1	CERTH	1.00
2	FEUP	8.00
3	ETH Zurich	0.00
4	TU Delft	15.00
5	TSI	18.00
6	Imperial	22.00
7	MST	11.00
8	APDL	0.00
9	CNRS	1.00
	Total	76.00

List of deliverables

Deliverable Number [61]	Deliverable Title	Lead beneficiary number	Estimated indicative person-months	Nature [62]	Dissemination level [63]	Delivery date [64]
D3.1	Synergetic/Cognitive Sonar AUV Communications	4	15.00	R	PU	15
D3.2	Photometric stereo through a strongly scattering medium	6	22.00	R	PU	22
D3.3	Cooperative AUV Localization	5	12.00	R	PU	12
D3.4	Collaborative Underwater Sensing	5	14.00	R	PU	14
D3.5	Surface estimation with photometric stereo and sonar	6	13.00	R	PU	13

List of deliverables

Delive-rable Number [61]	Deliverable Title	Lead benefi-ciary number	Estimated indicative person-months	Nature [62]	Dissemi-nation level [63]	Delivery date [64]
		Total	76.00			

Description of deliverables

D3.1) Synergetic/Cognitive Sonar AUV Communications: It will provide the details of the NOPTILUS communication system along with experimental results from Integration Week 1 [month 15]

D3.2) Photometric stereo through a strongly scattering medium: It will provide the details of the Photometric stereo through a strongly scattering medium along with experimental results. [month 22]

D3.3) Cooperative AUV Localization: It will provide the details of the NOPTILUS Cooperative Localization method along with experimental results [month 12]

D3.4) Collaborative Underwater Sensing: It will provide the details of the NOPTILUS MIMO/Cognitive Sonar along with experimental results [month 14]

D3.5) Surface estimation with photometric stereo and sonar: It will provide the details of the NOPTILUS sonar/vision fusion system along with experimental results [month 13]

Schedule of relevant Milestones

Milestone number [59]	Milestone name	Lead benefi-ciary number	Delivery date from Annex I [60]	Comments
MS2	Communications, vision and sonar-based mapping work as intended	5	30	Successful completion of real-life tests ruring Integration Week 2 and successful completion of the simulation-based evaluation
MS3	Localization, collaborative sensing, and fused vision/sonar work fully-functional, mounted on AUV	5	30	Tests during Integration Week 2, successful according to D8.1.

WT3:
Work package description

Project Number [1]	270180	Project Acronym [2]	NOPTILUS

One form per Work Package

Work package number [53]	WP4	Type of activity [54]	RTD
Work package title	Cooperative Distributed Estimation		
Start month	7		
End month	30		
Lead beneficiary number [55]	1		

Objectives

The focus of this work package is to successfully address the medium-level NOPTILUS objective (O7), by designing and developing all necessary NOPTILUS modules which – by receiving inputs from the modules developed in WP3 – will be able to
- Create static as well as dynamic high-fidelity 3D maps of the benthic environment.
- Accurately estimate and track the spatio-temporal evolution of dynamic processes of interest (e.g. spread of chemicals).

Description of work and role of partners

WP4 objective is to develop robust and scalable, decentralized nonlinear estimators for cooperative localization, mapping, and process tracking whose processing and communication requirements explicitly consider the availability of resources (i.e., CPU, memory, communication topology and bandwidth), and provide graceful degradation in the presence of failures. In particular, it will combine information from multiple heterogeneous sensing modalities (e.g., static or free floating underwater sensors and AUVs of various capabilities) that can be deployed efficiently and collaborate with each other, as well as with existing infrastructure (e.g., surface vessels, underwater sonars, etc) to provide measurements at different spatial and temporal scales. In this effort and in order to increase the system flexibility in terms of both processing and representation ability, estimation algorithms will be developed within WP4 that create and use Gaussian Processes-based (GPs) [E28, E2] representations of the benthic environment, i.e., for constructing 3D maps of the ocean floor, as well as for describing the spatio-temporal distribution of chemicals or other processes of interest. The main advantage of GPs is that, in contrast to grid-based representations, GPs scale linearly with the number of observations and their density can be adjusted to meet task requirements. Extending existing GP representations to adapt to time and resolution variations while considering the AUVs communication and processing constraints is within the main focus of WP4.
Additionally, and in contrast to existing SLAM algorithms that seek to create dense maps of uniform accuracy, WP4 will adopt a fundamentally different approach to develop Sonar-aided Inertial Navigation Systems (S-INS) where sonar observations (e.g., point features or patches) are treated differently based on their information content and localization utility to create maps of adjustable resolution and accuracy. In particular, most tracked features will be first processed, at only linear cost, to precisely estimate the motion of the vehicle [E21]. Subsequently, only a subset of them will be used for creating a sparse geo-referenced map which will be augmented, as needed, to contain additional mapping information at multiple scales and resolutions [E16].
The main advantages of this mapping process are (i) its computational cost can be adjusted seamlessly from linear to quadratic to match the availability of resources while making optimal use of them [E23, E24], and (ii) it provides the necessary flexibility for concentrating sensing and processing resources to areas along the motion direction that are critical for ensuring precise navigation (e.g., in the vicinity of obstacles). Moreover, and as an extension to cooperative localization of large teams of UAVs, WP4 will also employ decentralized estimators capable of optimally selecting the most informative measurements [E18] and processing severely quantized and compressed observations [E29, E22, E33] at computational cost an order of magnitude lower compared to centralized alternatives [E25, E26].
Furthermore, expansions of the recent work on extrinsic calibration [E35, E37, E14, E34, E7] will take place within WP4 to determine the relative position and attitude of groups of AUVs navigating in 3D using sensor-to-sensor observations, such as relative distance, bearing, and speed. This will endow teams of AUVs with the ability to efficiently and precisely fuse spatially distributed heterogeneous sources of information (e.g.,

chemical sensors, sonars, cameras, etc), while at the same time considering multiple realization of the estimated process (e.g., due to multiple local maxima [E32, E8]). This in turn, will allow human operators to access and manipulate collected information at multiple levels, in terms of scale, vantage point, and mode, hence resulting in increased situational awareness.
The measurements collected by the various sensors, will be communicated, using appropriate dimensionality reduction and quantization techniques [E29, E22, E33], and processed in a decentralized manner [E30] to estimate spatiotemporal processes of interest while making optimal use of the available memory and computational resources. This will become possible not only through appropriate sensor selection criteria (e.g., as the ones designed for cooperative localization [E18]), but also by introducing appropriate relaxations that lead to any-time algorithms as those introduced for SLAM [E23, E24] and cooperative localization [E25, E26]. Moreover, WP4 will leverage recent work on performance characterization [E19, E20, E13, E17] to derive analytical expressions for the lower bounds on the achieved accuracy as functions of key system and environment parameters, such as the number and precision of the sensors used, the distribution and number of features and targets in the environments, and the topology of the relative (i.e., between the sensors) measurement graph. These analytical results will be used for determining the appropriate team of AUVs that must be deployed, so as to achieve certain mission objectives (e.g., map a sunken ship or determine the spread of an oil leak), and for quantifying the loss of performance once approximations are introduced in the estimation process in order to preserve critical resources.
WP4 is subdivided in the following tasks:
Task 4.1. Cooperative Mapping
- Develop estimation algorithms that use and create Gaussian Process-based 3D representations of the benthic environment.
- Extension of existing GP representations to adapt to time and resolution variations while considering the AUVs' communications and processing constraints.
- Development of Sonar-aided Inertial Navigation System (S-INS) which efficiently processes sonar measurements according to their information content and localization utility.
- Development of algorithms for estimating relative AUV position and attitude based on sensor-to-sensor observations.
- Dimensionality reduction and quantization for communicating sensor measurements and implementing the estimation algorithms in a decentralized manner while making optimal use of available memory and computational recourses.
Task 4.2. Cooperative Process Tracking
- Develop estimation algorithms that use and create Gaussian Process-based 3D representations of dynamically evolving processes.
- Extension of existing dynamic GP representations to adapt to time and resolution variations while considering AUVs communications and processing constraints.
- Adaptation of S-INS and relative position/attitude algorithms of T4. to dynamic process estimation.
- Extensions of the algorithms for estimating relative AUV position and attitude of Task 4.1 to dynamic process tracking.
- Extensions of the algorithms for dimensionality reduction and quantization of Task 4.1 to dynamic process tracking.

Person-Months per Participant

Participant number [10]	Participant short name [11]	Person-months per participant
1	CERTH	30.00
2	FEUP	10.00
3	ETH Zurich	0.00
4	TU Delft	0.00
5	TSI	13.00
6	Imperial	12.00
7	MST	0.00

Person-Months per Participant

Participant number [10]	Participant short name [11]	Person-months per participant
8	APDL	0.00
9	CNRS	1.00
	Total	66.00

List of deliverables

Deliverable Number [61]	Deliverable Title	Lead beneficiary number	Estimated indicative person-months	Nature [62]	Dissemination level [63]	Delivery date [64]
D4.1	Cooperative AUV Static and Dynamic Mapping Construction	1	33.00	R	PU	30
D4.2	Cooperative AUV Dynamic Process Tracking	1	33.00	R	PU	30
		Total	66.00			

Description of deliverables

D4.1) Cooperative AUV Static and Dynamic Mapping Construction: It will provide the details of the NOPTILUS cooperative and distributed estimation for map construction along with experimental results [month 30]

D4.2) Cooperative AUV Dynamic Process Tracking: It will provide the details of the NOPTILUS cooperative and distributed estimation of dynamic processes along with experimental results [month 30]

Schedule of relevant Milestones

Milestone number [59]	Milestone name	Lead beneficiary number	Delivery date from Annex I [60]	Comments

WT3:
Work package description

Project Number [1]	270180	Project Acronym [2]	NOPTILUS

One form per Work Package

Work package number [53]	WP5	Type of activity [54]	RTD
Work package title	Motion and Sensory-Motor Control		
Start month	7		
End month	30		
Lead beneficiary number [55]	3		

Objectives

The focus of this work package is to successfully address the medium-level NOPTILUS objective (O8), by designing and developing all necessary NOPTILUS modules for
- Performing robust and efficient motion (state-space trajectory following) control;
- Performing robust and efficient sensory-motor control for the case of poor (or unavailable) global localization; i.e., when it is not feasible to perform state-space trajectory following control;
- Switching appropriately and efficiently among the two control options.
- Develop a safety-control mechanism for the AUV collision avoidance.

Description of work and role of partners

WP5 is subdivided in the following tasks:
Task 5.1. Motion Control
- Combine the recently developed – within the FP7 project Co3AUVs – non-adaptive and non-learning motion control strategies of [M12], [M13] with the concurrent exploitation–exploration scheme of [M9]–[M11].
- Investigate and develop efficient methods for combining the control strategies of [M12], [M13] with the concurrent exploitation–exploration scheme of [M9]-[M11].
- Perform extensive simulation studies (using realistic, high-fidelity underwater simulation models) to determine optimal combination strategies to be adopted within the NOPTILUS system.
- Perform (during Integration Week 2) real-life experiments in the NOPTILUS Test Case (involving both single-AUV motion control and coordinated multi-AUV motion control), using competing combination strategies, and selecting the strategy to be finally adopted within NOPTILUS.
Task 5.2. Sensory-Motor Control
- Integration of sonar measurements into a probabilistic framework for localization and sensory-motor control.
- Modeling of the perception uncertainties resulting from sonar measurements and integration into a generative probabilistic model (Input from WP4). The trajectory-tracking system will have to use either only sonar or a combination of sonar and active vision to define the trajectory and localize the system with respect to it. The use of sonar with natural landmarks is likely to introduce a lot of uncertainty in the localization. The proper modeling of these uncertainties will require a strong collaboration with the NOPTILUS methodologies for Situation Understanding (objective (O1)).
- Sensory-motor trajectory tracking in the presence of currents: modeling of the system's dynamics within the control framework, obstacle detection and obstacle avoidance. (Strong link with Task 5.1). Tracking the reference trajectory in the presence of currents will be significantly more challenging for an AUV as compared to a car-like robot. Thus, it will be necessary to introduce a model of the system's dynamics in the control framework, while still accounting for possible obstacles. This aspect will require tight integration with the NOPTILUS Motion Control Design (Task 5.1).
- Development of a self-diagnosis framework adapted to underwater sonar perception: evaluation of trajectory-following performance. The self-diagnosis presented in [S9] is not directly applicable to systems that rely on im-precise sonar sensors for perceiving their underwater environment. Thus, additional effort will have to be devoted to monitoring the quality of the trajectory tracking. In particular, when the system is initialized, several time indices in the sensory-motor trajectory could match the current observation. In this case, the system will need to actively choose to move until it gathers sufficient information about its correct spatio-temporal localization. To address all these issues, significant advances in the areas of active localization and performance monitoring will be core contributions of the NOPTILUS project.

- Active perception during initialization: when the system is initialized, several time indices in the sensory-motor trajectory could match the current observation. In this case, the system will actively move so as to gather suffi-cient information for disambiguating its spatio-temporal localization.
Task 5.3. Motion/Sensory-Motor Control Switching Mechanism and Safety Mechanism
The purpose of this task is two-fold:
(1) to devise an appropriate mechanism for switching to/from sensory-motor AUV control from/to state-space motion AUV control when localization accuracy deteriorates/improves, and
(2) to design a collision-avoidance controller which will be activated whenever there is a possibility for the AUV to collide with an obstacle, the sea-floor, or another AUV (due to e.g. instabilities introduced in the AUV motion caused by currents, turbulences or, even, the switching mechanism).
There are two issues of concern regarding the switching mechanism: (a) in many cases it is difficult to estimate when (and at which level) the localization accuracy has become poor; (b) we may face situations where only some of the AUVs exhibit poor localization performance. As there exist no theoretical or practical tools to address these two issues, a parameterized switching mechanism will be developed and its parameters will be optimized through a standard reinforcement learning procedure firstly in simulations and then experimentally (in the NOPTILUS Test Case, during Integration Week 2) by exposing the NOPTILUS multi-AUV system to various underwater conditions and different team configurations. The performance criterion – to be used in the reinforcement learning procedure – will be a measure of the success of the switching system to accomplish a particular estimation task (e.g. mapping of a complex benthic environment). The parameterized switching mechanism will be further optimized before the final demonstration of the system (Integration Week 3) again by employing reinforcement learning but this time by using as a performance criterion a measure of the success of the switching system to accomplish a particular recognition and situation understanding task during the regular operation of the overall NOPTILUS system in the NOPTILUS Test Case.
Regarding the second issue, the collision-avoidance controller will be designed based on the same design principles as the motion controller of Task 5.1. The difference in this case is that the objective is not to track a path, but rather to keep the AUVs at a distance from all observed obstacles that is larger than a safety margin. Hence, there is no need to accurately localize the AUV, with respect to a global frame of reference, but rather to be able to accurately measure the AUV-obstacle distance. As in the case of Task 5.1, a well-established – non-adaptive, non-learning – collision-avoidance controller will be enhanced with the concurrent exploitation-exploration learning methodology of [M9]-[M11]; (a) extensive simulation studies (using realistic, high-fidelity underwater simulation models) and (b) real-world experiments in the NOPTILUS Test Case (during Integration Week 2), will be performed to determine the most efficient combination strategy between the two control schemes.

Person-Months per Participant

Participant number [10]	Participant short name [11]	Person-months per participant
1	CERTH	10.90
2	FEUP	6.00
3	ETH Zurich	14.40
4	TU Delft	0.00
5	TSI	0.00
6	Imperial	1.00
7	MST	6.00
8	APDL	0.00
9	CNRS	14.00
	Total	52.30

List of deliverables

Delive-rable Number [61]	Deliverable Title	Lead benefi-ciary number	Estimated indicative person-months	Nature [62]	Dissemi-nation level [63]	Delivery date [64]
D5.1	Cooperative AUV Motion Control	1	11.90	R	PU	30
D5.2	AUV Sensory-motor control	3	30.40	R	PU	30
D5.3	Switching Motion/Sensory-motor control	3	10.00	R	PU	30
		Total	52.30			

Description of deliverables

D5.1) Cooperative AUV Motion Control: It will provide the details of the NOPTILUS motion control design along with experimental results [month 30]

D5.2) AUV Sensory-motor control: It will provide the details of the NOPTILUS sensory-motor control design along with experimental results [month 30]

D5.3) Switching Motion/Sensory-motor control: It will provide the details of the NOPTILUS switching control mechanism as well as the experimental results obtained through the application of reinforcement learning [month 30]

Schedule of relevant Milestones

Milestone number [59]	Milestone name	Lead benefi-ciary number	Delivery date from Annex I [60]	Comments

WT3:
Work package description

Project Number [1]	270180	Project Acronym [2]	NOPTILUS

One form per Work Package

Work package number [53]	WP6	Type of activity [54]	RTD
Work package title	Situation Understanding		
Start month	7		
End month	42		
Lead beneficiary number [55]	5		

Objectives

Situation Understanding is a crucial cognitive ability for the NOPTILUS multi-AUV system. Efficient machine learning approaches combined with flexible representations provide a framework of high potential that has not been explored in the context of high-level recognition, detection, and prediction. The focus of this work package is to successfully address the high-level NOPTILUS objective (O1), by designing and developing all necessary NOPTILUS modules for detecting, recognizing, understanding, and predicting static underwater features and patterns, as well as highly dynamic phenomena and events taking place and influencing the underwater operations. Machine learning methodologies, reinforcement learning tools and probabilistic context-free grammars will be exploited in innovative ways and will be combined with a rich set of experimental observation logs from human-operated underwater missions, towards the development of cognitive-based "Learning from Past Data" and of structured-prediction designs capable of successfully addressing the objective of this WP.

Description of work and role of partners

The purpose of this WP is to leverage the information provided by the NOPTILUS Cooperative Distributed Estimation Module of WP4 (i.e. static and dynamic 3D underwater maps and geometric characteristics of dynamic underwater processes) to (a) recognize sequences of interest in this stream of information which may signal the presence or the initiation of a particular event, for example the approach of a moving obstacle or the extend of a leak, and (b) infer possible evolutions of an on-going event and use this prediction to assist decision making, for example estimate the time to a possible collision (and therefore take action to avoid it) or the direction of a spreading spill (and therefore indicate where to apply chemical neutralizers).To support these operations, we plan to exploit existing technologies and combine them in innovative ways in order to achieve our goal, as described in the following Tasks.
Task 6.1. "Learning from Past Data" Design
To address the problem of situation understanding we choose to combine models, such as probabilistic context-free grammars (PCFGs) [U0], with machine learning techniques (unsupervised learning and reinforcement learning). PCFGs offer a concise way of modeling and representing compactly a multitude of complex sequences ("sentences") that share a common internal structure. PCFGs have been used widely in natural language processing, but closer to our context, PCFGs have been successfully applied for recognizing action sequences from visual data with the purpose of detecting patterns of human activity [U1], [U2]. Building on this work, our intention is to appropriately adopt the "Grammars of Human Behavior" framework [U3] to the particular problem addressed in this task. Given an appropriate grammar specification, a Viterbi-like observation parser can be used to recognize interesting observation sequences within a rolling time window and therefore flag the presence of an event in real-time. The challenge here is to define an appropriate "alphabet" that is the atomic/base observations which can potentially form sequences associated with the target event. This "alphabet" will have to strike a balance between expressiveness and compactness and will have to rely on fused data from multiple AUVs, as described above. The specification of the grammar rules can be done manually, but even more interestingly the production rules could be induced automatically using machine learning. During a learning phase, recorded logs of past missions labeled correctly can be used in a variant of the Expectation-Minimization (EM) algorithm [U4] that uses the Inside/Outside (IO) algorithm [U5] to infer rules that capture the internal structure of observation sequences related to an event of interest in the maximum likelihood sense. The high computation cost of the EM/IO algorithm may be prohibitive for real-time operation. An alternative efficient grammar learning approach is based on reinforcement learning [U6]. Several observation logs from human-operated underwater missions are already available from the Portuguese partners, but new

more focused logs will be acquired from subsequent missions so as to improve the system's performance. Notice that the same log can and will be used multiple times to test various candidate "alphabets" of base observations and identify the best level of abstraction. Realistically, we do not intend to infer a single grammar for all possible underwater events, but rather different grammars for events related to different missions, e.g. detecting leakages from a shipwreck vs. tracking behavior patterns in marine life.
Task 6.2. Learning Structured Prediction
An alternative is based on a view of the situation understanding problem as a structured prediction problem, whereby a collection of input objects (observations) need to be mapped to a predicted structured object (event = certain sequences of observations). In its most generic form, this is a typical supervised learning problem; the desired mapping can be learned using a correctly labeled set of input-prediction training data and a loss function that evaluates the quality of a mapping. This monolithic approach, however, does not take advantage of the inherent structure found in the predictions and therefore requires a large number of training data to compensate for this inflexibility. A recent research trend [U7], [U8] in the area of structured prediction reduces the problem to a sequential decision problem, whereby the predicted structured object for a given input is built incrementally making one decision at a time. Therefore, instead of modeling what a good prediction looks like, this sequential approach directly models how to build a good prediction. Finding the optimal policy for the resulting Markov Decision Process (MDP) of this reduction is equivalent to finding the mapping that minimizes the loss function. A illustrative example of this approach is given in [U9]: let Y represent the prediction of the handwritten word X which is the handwritten word STRUCTURE with a mark on the letters UR (making them partly invisible). In the traditional formulation, the 9 hand-written letters are mapped directly to the predicted word STRUCTURE, whereas in the sequential formulation the prediction is built letter-by-letter. The reduction described above is not practical on its own, given that the full model of the MDP is either huge or totally unknown. However, it is important because it opens the door to using a wide variety of successful reinforcement learning (RL) methods [U10], [U11], which can learn approximate policies without a model. Briefly, RL is learning by trial-and-error; the system observes the current state, takes an action, receives a reward or penalty, observes the next state, etc. and through these samples of interaction eventually learns a good policy (choosing actions in each state) that maximizes the expected long-term reward. Our intention is to adapt advanced RL algorithms, such as Least-Squares Policy Iteration (LSPI) [U11] and Rollout-Sampling Policy Iteration (RSPI) [U12], and apply them in the NOPTILUS context. It is expected that both LSPI and RSPI will produce superior results compared to their standard counterparts, such as Q-learning and SARSA. Yet another related approach [U13] relies on a reduction of the structured prediction problem to inverse reinforcement learning (IRL), whereby the agent observes an optimal policy and attempts to learn the unknown reward function of the MDP which would lead to the observed policy, if solved optimally. In this case, a parser is trained directly on the data. Observation logs from human-operated underwater missions can also be used with the RL approaches to obtain training samples. The learned compact policy in either case can be used to "parse" the observation sequences.
Task 6.3. Combining "Learning from Past Data" and Structured Prediction
The rich set of available data from human-operated underwater operations collected by the 3 Portuguese partners in the past, as well as NOPTILUS data to be collected during the life-time of NOPTILUS will not be used only for learning/training purposes but also to evaluate/refine the two designs of Tasks 6.1 and 6.2 and develop the final Situation Understanding strategy (module) of NOPTILUS. Based on the evaluation of the two designs, a module combining the two designs will be developed. Depending on the efficiency of each design in particular situations, this composite module will either select the results of the one of the designs (using an arbitrator) or efficiently fuse them (using an estimator).

Person-Months per Participant

Participant number [10]	Participant short name [11]	Person-months per participant
1	CERTH	3.00
2	FEUP	2.00
3	ETH Zurich	0.00
4	TU Delft	0.00
5	TSI	29.00
6	Imperial	3.00

Person-Months per Participant

Participant number [10]	Participant short name [11]	Person-months per participant
7	MST	4.00
8	APDL	0.00
9	CNRS	0.00
	Total	41.00

List of deliverables

Deliverable Number [61]	Deliverable Title	Lead beneficiary number	Estimated indicative person-months	Nature [62]	Dissemination level [63]	Delivery date [64]
D6.1	Learning from Past Missions Design for multi-AUV Situation Understanding	5	18.00	R	PU	36
D6.2	Structured Prediction for multi-AUV Situation Understanding	5	14.00	R	PU	36
D6.3	Combining Learning from Past Missions and Structured Prediction Designs for multi-AUV Situation Understanding	5	9.00	R	PU	42
		Total	41.00			

Description of deliverables

D6.1) Learning from Past Missions Design for multi-AUV Situation Understanding: It will provide the details of the NOPTILUS situation understanding design that employs the “Learning from Past Data” methodology as well as the results obtained through the application of the learning procedure using available human-operator data. [month 36]

D6.2) Structured Prediction for multi-AUV Situation Understanding: It will provide the details of the NOPTILUS situation understanding design that employs the structured prediction methodology, as well as the results obtained through the application of the learning procedure using available human-operator data. [month 36]

D6.3) Combining Learning from Past Missions and Structured Prediction Designs for multi-AUV Situation Understanding: It will provide the details of the evaluation of the designs of Tasks 6.1 and 6.2, as well as the final NOPTILUS situation understanding module (that combines the two designs), along with experimental results. [month 42]

Schedule of relevant Milestones

Milestone number [59]	Milestone name	Lead beneficiary number	Delivery date from Annex I [60]	Comments

Project Number [1]	270180	Project Acronym [2]	NOPTILUS

One form per Work Package

Work package number [53]	WP7	Type of activity [54]	RTD
Work package title	Optimal Planning, Assignment and Navigation		
Start month	7		
End month	42		
Lead beneficiary number [55]	5		

Objectives

The focus of this work package is to successfully address the high-level NOPTILUS objective (O1), by designing and developing all necessary NOPTILUS modules for providing in real-time, arbitrarily-close-to-optimal, scalable, cooperative and distributed AUV Planning, Assignment and Navigation (PAN), by computing – in real-time and fully autonomously – the AUVs' motion strategy that
- given the physical, communication, computation, etc system constraints and limitations and
- by making optimal use of the available energy, memory and computational recourses;
(a) maximizes the acquired information and accuracy of the particular distributed estimation, recognition and situation understanding task(s) the NOPTILUS system has been deployed for;
(b) minimizes the time and processing required for accomplishing the aforementioned estimation, recognition and situation understanding task(s).

Description of work and role of partners

As already mentioned in Section B1.2.9, the NOPTILUS PAN module will be based on a recently introduced motion strategy [O23]-[O25] that needs to be significantly modified and extended to be suitable for the NOPTILUS concept. Next we describe the extensions and modifications required towards this goal.
Motion Strategies for optimizing not only Estimation but also Recognition and Situation Understanding. As is the case for most motion strategy designs (e.g. [O1]-[O22] and the references therein), the convex approach of [O23]-[O25] maximizes the estimation accuracy of a particular application, i.e., it addresses the problem of optimally designing the vehicles' trajectories so that the location of all static or moving landmarks, features, obstacles, etc is estimated with the maximum possible accuracy. However, in order to design and develop a completely autonomous system, the NOPTILUS PAN should be able to address the significantly more complex and challenging task of maximizing the ability of the overall system to recognize, understand, and predict static features and patterns, as well as dynamic phenomena and events. In other words, the NOPTILUS PAN module should be able to assign and navigate the AUVs so that the NOPTILUS Situation Understanding module (WP6) maximizes its recognition and situation understanding capabilities. This will be made possible – in close cooperation with WP6 – by appropriately updating the method of [O23]-[O25] which is based on optimal control principles. Specifically, the convex approach of [O23]-[O25] will have to be re-designed by replacing the estimation accuracy optimization criterion by a suitable criterion that corresponds to the ability of the Situation Understanding module to efficiently and accurately recognize, understand, and predict static features and patterns, as well as dynamic phenomena and events. Special attention will be given to the selection of such a criterion as well as to the overall re-design process so as to preserve the convexity properties of the original formulation.
Dealing with multi-task situation-awareness applications. The approach of [O23]-[O25] has been developed for single-task situation awareness applications such as exploration, mapping, and target tracking. However, in order to have a completely autonomous underwater system capable of successfully taking over tasks such as the ones described in Section B1.1.1, the NOPTILUS system should be able to perform multi-task operations e.g. by sending some of its AUVs to detect the shipwreck's damaged/leaking areas and by assigning other AUVs to locate and track the spread of chemicals. Apparently such a multi-task assignment has to be done in an optimal (or nearly optimal) fashion so that time and recourses are not wasted due to inefficient task assignment. In order to support multi-task situation-awareness operations, the approach of [O23]-[O25] should be revised and re-designed appropriately in order to incorporate multiple optimization criteria and, most importantly, discrete decision variables (i.e. for assigning AUVs to different tasks). The approach of [O23]-[O25], as it stands now,

allows only for continuous decision variables, which correspond to the control inputs or the position and attitude of each AUV. Special attention has to be given when incorporating discrete decision variables so as not to affect the convex nature of the overall design.
Assessing and considering the case of AUV re-surfacing, exploiting swarm motion to disambiguate, etc in cases of poor localization accuracy. The incorporation of discrete decision variables will also allow for the NOPTILUS PAN module to take into consideration, in its optimal decision-making mechanisms, the possibility to pursue one of the localization-improvement measures of Task 3.3 (Cooperative Underwater Localization). Specifically, during each time step, the NOPTILUS PAN module will consider multiple alternatives, such as to send some AUVs to directly explore the underwater environment, re-surface one or more AUVs to acquire a GPS fix, or exploit swarm motion to disambiguate position and attitude, according to the results of Task 3.3.
Re-design when sensory-motor control is activated. One of the key challenges in the success of the NOPTILUS PAN module, as well as of the overall NOPTILUS system, will be its ability to efficiently and robustly manage situations where sensory-motor control is activated. When state-space motion control is active (i.e. the localization accuracy of the NOPTILUS AUVs is satisfactory), the NOPTILUS PAN module transmits its desired AUV trajectories (state-space locations and attitudes) to the motion control module which takes over to ensure that these trajectories are accurately followed by the AUVs. However, when the sensory-motor control is active it is not possible for the NOPTILUS PAN module to transmit state-space trajectories to the AUVs, as these are of no use anymore. Instead, a different model for the multi-AUV/external environment system has to be considered which incorporates knowledge of the form “the perception of the AUV x for the landmark b is y”, instead of the current approach – applicable when motion control is active – which assumes knowledge of the form “the relative pose (position/attitude) of the AUV a with respect to landmark b is y”. Special effort will be made within this task to develop and validate such a model (based on geometric principles, perceptual modeling and experimental data to be collected from the NOPTILUS Test Case) and to incorporate it within the NOPTILUS PAN design.
Dealing with totally unstructured and highly-varying environments: Real-time Cognitive-based Adaptive Re-design of Motion Strategy Decision-making Mechanisms. The approach of [O23]-[O25] is applicable to cases where the external environment has little or predictable effect on the multi-vehicle system dynamics. While this is the case in the multi-UAV system of the sFLY project (which employs advanced mechanical and control designs and operates only in low-turbulence/wind environments), it cannot be used for NOPTILUS which will have to cope with a totally unstructured and rapidly changing environment and with the significant effect of exogenous disturbances, obstacles, etc. To overcome this problem, we plan to combine the approach of [O23]-[O25] with the recently introduced Cognitive-based Adaptive Optimization (CAO) methodology – originally developed for the cognitive-based on-line fine-tuning of large-scale control systems [O26]-[O28]– as follows:
1. the CAO methodology will be used to adaptively and in real-time learn the effect of the external environment variations to the overall multi-AUV system dynamics;
2. based on the information provided by CAO, the convex approach will continuously re-design the PAN decision-making mechanisms.
Note that the efficient performance and rapid convergence of CAO, when applied to generic large-scale control systems and decision-making mechanisms of arbitrary complexity and scale, has been established both by means of rigorous mathematical arguments and extensive experiments [O26]-[O28]. Moreover, as part of the FP7 ICT projects PEBBLE and AGILE, the CAO approach is currently used for the fine-tuning of large-scale control and sensor systems in many different energy-efficient buildings and traffic control systems. At this point, we should also mention that the CAO approach belongs to the family of “Learning using Exploration” (LuE) adaptive optimization methods such as some types of reinforcement learning, actor-critic, Q-learning, etc methodologies. LuE methodologies possess certain advantages as compared to alternative methods: they require no a priori knowledge or severe assumptions/constraints on the system/environment they operate in and they are robust and computationally efficient. The main advantage of CAO over other LuE methods lies in its computational simplicity (while most of the existing LuE methods are quite time-consuming) and its guarantee of providing rapid convergence and safe performance. In contrast, most of the existing LuE methods suffer from slow convergence and/or very poor performance while the learning process is active.
Special care has to be taken in order to appropriately and successfully combine the CAO approach with the convex motion strategy design of [O23]-[O25]. This is due to the fact that the CAO approach requires perturbing the original AUV trajectories computed by the convex approach in order to guarantee that all characteristics of the unknown environment are sufficiently explored. Due to the strict NOPTILUS constraints and requirements, such a “perturbation” should be as small as possible and without putting the stability and robustness of the overall system at risk.
Dealing with strict recourse, communication, sensing, physical and processing constraints as well as requirements imposed by the design of the other NOPTILUS modules.
A final, but quite crucial, step in the PAN design is the incorporation of all types of requirements and constraints

im-posed in the NOPTILUS multi-AUV system. There are two categories of such requirements and constraints:
1. The first category involves requirements imposed by the design of the other NOPTILUS modules, such as the requirement for “mating” AUVs in the virtual MIMO sonar approach of Task 3.4 or the collaboration requirements in the NOPTILUS underwater communication system.
2. The second category involves all types of constraints imposed by the particular nature and limitations of a multi-AUV system: obstacle avoidance, energy consumption-related and maximum/minimum speed constraints, communication and processing constraints with special emphasis on distributed computation constraints that are imposed due to either processing limitations of each AUV, or the fact that some of the AUVs cannot communicate with all other team members.
As the convex approach of [O23]-[O25] is based on optimal control principles, it allows incorporating a large variety of constraints. However, as the constraints and requirements of underwater applications are particularly strict, special attention should be given so as to avoid hindering the scalability of the overall scheme.
WP7 is subdivided in the following tasks:
Task 7.1. Arbitrarily-close-to-optimal, Scalable multi-AUV Motion Strategies for Multi-Task Estimation, Recognition and Situation Understanding
- Re-design and update the convex approach of [O23]-[O25] for Estimation as well as Recognition and Situation Understanding Optimization.
- Incorporate discrete decision variables in the optimal motion strategy design to allow for multi-task situation awareness operations as well as
- AUV re-surfacing, swarm motion exploitation to disambiguate location, etc according to the results of Task 3.3.
- Develop a model appropriate for PAN when sensor-motor control is active and re-design the NOPTILUS PAN module to incorporate such a model.
Task 7.2. Real-time Cognitive-based Adaptive Re-design of Motion Strategies
Combine the CAO approach with the convex motion strategy design of the previous Task for the cognitive-based adaptation and on-line re-design of the motion strategy decision making mechanisms.
Task 7.3. Incorporating Physical, Communication, and Processing Constraints
Update and revise the motion strategy module of the previous tasks by incorporating
- Requirements imposed by the design of the other NOPTILUS modules, such as the Underwater Communications and Underwater Sensing Modules of WP3.
- Physical, communication, sensing, and processing constraints such as obstacle avoidance, energy consumption-related and maximum/minimum speed constraints, communication and processing constraints.
Task 7.4. Interfacing with the rest of NOPTILUS Modules
As the NOPTILUS PAN (software) module is the central module of NOPTILUS, appropriately interfacing it with the rest of the NOPTILUS (software) modules is required. Moreover and to ensure the proper and reliable functioning of the integrated NOPTILUS software system before its deployment to the real-world situations, extensive verification tests will be conducted at the simulation level and through controlled experiments.

Person-Months per Participant

Participant number [10]	Participant short name [11]	Person-months per participant
1	CERTH	38.00
2	FEUP	9.00
3	ETH Zurich	0.00
4	TU Delft	4.00
5	TSI	8.00
6	Imperial	3.00
7	MST	6.00
8	APDL	0.00
9	CNRS	0.00
	Total	68.00

List of deliverables

Delive-rable Number [61]	Deliverable Title	Lead benefi-ciary number	Estimated indicative person-months	Nature [62]	Dissemi-nation level [63]	Delivery date [64]
D7.1	The NOPTILUS Planning, Assignment and Navigation Module (PAN with CAO algorithm)	1	37.00	R	PU	36
D7.2	The NOPTILUS Planning, Assignment and Navigation Module (incorporating underwater constraints and integrating with the Situation Understanding Module)	1	20.00	R	PU	42
D7.3	The overall NOPTILUS software system	1	11.00	R	PU	42
		Total	68.00			

Description of deliverables

D7.1) The NOPTILUS Planning, Assignment and Navigation Module (PAN with CAO algorithm): It will provide the details of the NOPTILUS PAN module incorporating the CAO algorithm [month 36]

D7.2) The NOPTILUS Planning, Assignment and Navigation Module (incorporating underwater constraints and integrating with the Situation Understanding Module): It will provide the details of the NOPTILUS PAN module incorporating underwater constraints and integrating with the Situation Understanding Module [month 42]

D7.3) The overall NOPTILUS software system: It will provide the details of the overall NOPTILUS PAN module along with its interfaces with the other NOPTILUS modules [month 42]

Schedule of relevant Milestones

Milestone number [59]	Milestone name	Lead benefi-ciary number	Delivery date from Annex I [60]	Comments
MS4	Cooperative mapping and control modules work fully-functional, mounted on AUV systems	1	42	Tests during Integration Week 3, successful according to D8.1.

WT3:
Work package description

Project Number [1]	270180	Project Acronym [2]	NOPTILUS

One form per Work Package

Work package number [53]	WP8	Type of activity [54]	RTD
Work package title	System Integration and Evaluation		
Start month	1		
End month	48		
Lead beneficiary number [55]	7		

Objectives

The objective of this WP is the integration, validation, demonstration and evaluation of the entire NOPTILUS system with the aim of establishing that the NOPTILUS system can be used for 24hour/7day-a-week persistent underwater data collection in harbour areas. This is will be done in accordance to the IEEE Standard 1220-2005 for the systems engineering process. The task decomposition follows from this development strategy.
The demonstration scenarios involve 3 basic test scenarios as well as missions to be defined during project's lifetime (see section B1.1.4). There will also be a component of 24/7 persistence. Data from manned operations will be used as a baseline for the evaluation of the developments.
The test scenarios will be developed incrementally. This will be done in close cooperation with the end-user, APDL, and according to an evaluation plan to be developed in this WP. Lessons learned from the first deployments will be transitioned to operational procedures for performance improvement. This will test the limits of the system and of its operational capabilities.
Demonstrations will take place incrementally. The demonstration matrix includes entries for the type of operations (or combinations of those) versus the type of components used (or combinations of those).

Description of work and role of partners

MST will lead WP8 in close cooperation with the other partners: APDL will provide the facilities, measures of performance and effectiveness, data sets from traditional (manned) operations, and recommendations for improvements. MST and FEUP will manage experiments and operations with the assistance of other partners. Each partner will test and evaluate his/her developments, first component-wise, and later in an integrated fashion.
WP8 is subdivided in the following tasks:
Task 8.1. Development of an evaluation methodology
The work to be carried within task 8.1 concerns the development of an evaluation methodology for the NOPTILUS system. This entails the development of scenarios of operation, use cases, operational and environmental conditions, measures of performance, and measures of effectiveness. There will be component and system-level evaluations. The baseline will be provided by data collected in "traditional" operations which APDL is required to perform to conform to the regulations.
Task 8.2. Integration of fixed components
This task concerns the integration of gateway buoys, moored sensors, communications and control centre. This entails several integration steps leading towards the 24/7 operation of the system.
Task 8.3. AUV systems' integration
This task concerns the integration of the developments from the other work packages on the autonomous underwater vehicles to be used in the project. This is one of the most challenging tasks in this WP. This consists of:
- Development of AUV systems' integration plan.
- Integration of communication systems.
- Integration of sonar systems.
- Integration of advanced control and navigation systems.
- Integration of localization systems.
- AUV system performance measurement.
Task 8.4. ASV systems' integration
This task concerns the integration of the developments from the other work packages on the autonomous

surface vehicles to be used in the project. This consists of:
- Development of ASV systems' integration plan.
- Integration of communication systems.
- Integration of sonar systems.
- Integration of advanced control and navigation systems.
- ASV system performance measurement.

Task 8.5. Systems integration
This task concerns the integration of the NOPTILUS systems from the previous tasks. This is especially focused on communications, advanced control and navigation, and coordination. This consists of:
- Development of an integration plan.
- Integration of communication networks.
- Integration of multi-vehicle control and navigation systems.
- NOPTILUS system performance assessment.
- Assessment of the value of cooperation.

Task 8.6. Demonstration and Evaluation
This task concerns the evaluation and demonstration of the NOPTILUS system that will take place both during Inte-gration Weeks 1-3 (test and evaluation of NOPTILUS components and sub-systems) and during the final demonstration period (M42-M48). The test scenarios are described in section B1.1.4 and the measurable objectives the NOPTILUS system is called to meet in section B1.1.5. Further detailing of the scenarios and objectives will be done as parts of the Task 8.1.

Person-Months per Participant

Participant number [10]	Participant short name [11]	Person-months per participant
1	CERTH	14.00
2	FEUP	44.00
3	ETH Zurich	0.00
4	TU Delft	5.00
5	TSI	9.00
6	Imperial	8.00
7	MST	57.00
8	APDL	26.00
9	CNRS	4.00
	Total	167.00

List of deliverables

Delive-rable Number [61]	Deliverable Title	Lead benefi-ciary number	Estimated indicative person-months	Nature [62]	Dissemi-nation level [63]	Delivery date [64]
D8.1	Evaluation Methodology and Definition of Accuracy/Efficiency Targets	7	10.00	R	PU	12
D8.2	Fixed components	7	10.00	R	RE	24
D8.3	AUV System	7	20.00	R	RE	36
D8.4	ASV System	7	13.00	R	RE	30

List of deliverables

Delive-rable Number [61]	Deliverable Title	Lead benefi-ciary number	Estimated indicative person-months	Nature [62]	Dissemi-nation level [63]	Delivery date [64]
D8.5	NOPTILUS System (hardware and software)	7	41.00	R	RE	42
D8.6	Demonstration and evaluation report	2	73.00	R	PU	48
		Total	167.00			

Description of deliverables

D8.1) Evaluation Methodology and Definition of Accuracy/Efficiency Targets: This will provide the evaluation methodology for the NOPTILUS systems and for its individual components. [month 12]

D8.2) Fixed components: The system along with a document reporting all developments, providing user manuals for the operation of these components, and presenting the performance metrics. [month 24]

D8.3) AUV System: The system along with a document reporting all developments, providing user manuals for the operation of these components, and presenting the performance metrics. [month 36]

D8.4) ASV System: The system along with a document reporting all developments, providing user manuals for the operation of these components, and presenting the performance metrics. [month 30]

D8.5) NOPTILUS System (hardware and software): The system along with a document reporting all developments, providing user manuals for the operation of these components, and presenting the performance metrics [month 42]

D8.6) Demonstration and evaluation report: This reports the evaluation of the system, discusses lessons learned, and describes the demonstrations that took place throughout the duration of the project. [month 48]

Schedule of relevant Milestones

Milestone number [59]	Milestone name	Lead benefi-ciary number	Delivery date from Annex I [60]	Comments
MS5	Successful operation/communication of all NOPTILUS hardware/software components	7	43	Successful operation of the overall NOPTILUS system during Demonstrations according to D8.1
MS6	Successful finalization of demonstrations	1	48	Successful completion of Demonstrations according to D8.1

WT3:
Work package description

Project Number [1]	270180	Project Acronym [2]	NOPTILUS

One form per Work Package

Work package number [53]	WP9	Type of activity [54]	MGT
Work package title	Dissemination, Training and Exploitation		
Start month	1		
End month	48		
Lead beneficiary number [55]	2		

Objectives

To broadly disseminate the project results
To successfully prepare the exploitation of new products
To provide training material and train researchers and potential users of the system

Description of work and role of partners

Task 9.1: Dissemination Activities
- Dissemination and Exploitation Plan
- Project Leaflet
- Project Website
- Short Video demonstrating NOPTILUS
- A CD-ROM with informative content regarding NOPTILUS.
- Formation of the Underwater Vehicle User Group and continuous communication with its members requesting their inputs and updating them about the NOPTILUS's advances.
- Workshops of the Underwater Vehicle User Group and organization of technology transfer meetings
- Presentation in international conferences
- Publications in international journals
- Organization of a least one international workshops in conjunction with a major Conference
- Organization of at least one event in cooperation with strongly-related EC-funded projects (e.g. CO3AUV, TRIDENT)
- Cooperation with EURobotics and EUCognition coordinated actions
- Participation at a least one international fair
- Open-house fairs

Task 9.2: Exploitation Activities
- Identification of innovative products
- Development of exploitation plans for products
- Preparation and updates of the Dissemination and Use of Foreground

Task 9.3: Training Activities
- Summer Schools
- Training/Educational Material.

Person-Months per Participant

Participant number [10]	Participant short name [11]	Person-months per participant
1	CERTH	3.00
2	FEUP	6.00
3	ETH Zurich	0.00
4	TU Delft	3.00
5	TSI	5.00

Person-Months per Participant

Participant number [10]	Participant short name [11]	Person-months per participant
6	Imperial	3.00
7	MST	6.00
8	APDL	3.00
9	CNRS	3.00
	Total	32.00

List of deliverables

Deliverable Number [61]	Deliverable Title	Lead beneficiary number	Estimated indicative person-months	Nature [62]	Dissemination level [63]	Delivery date [64]
D9.1	NOPTILUS Website, Video, CD-ROM and project-leaflet	2	2.00	O	PU	3
D9.2.1	Dissemination and Use of Foreground (1st version)	2	2.00	R	PP	6
D9.2.2	Dissemination and Use of Foreground (2nd version)	2	9.00	R	PP	48
D9.3	Open-House Fairs at NOPTILUS Test Case	2	4.00	O	PU	48
D9.4	Scientific Publications, Summer Schools, Training Material, Organization of Conferences, Workshops and Technology Transfer Meetings	2	15.00	O	PU	48
		Total	32.00			

Description of deliverables

D9.1) NOPTILUS Website, Video, CD-ROM and project-leaflet: The NOPTILUS Website, Video, CD-ROM and project-leaflet [month 3]

D9.2.1) Dissemination and Use of Foreground (1st version): It will report the 1st version of the project's plans for dissemination and exploitation [month 6]

D9.2.2) Dissemination and Use of Foreground (2nd version): It will report the 2ndversion of the project's plans for dissemination and exploitation [month 48]

D9.3) Open-House Fairs at NOPTILUS Test Case: Open-House Fairs at NOPTILUS Test Case, where visitors will have the opportunity to watch the NOPTILUS system ion operation [month 48]

D9.4) Scientific Publications, Summer Schools, Training Material, Organization of Conferences, Workshops and Technology Transfer Meetings: Collection of all NOPTILUS' Scientific Publications, Summer Schools Material and Minutes, Training Material, Conferences and Workshops Proceedings and Minutes of Technology Transfer Meetings [month 48]

Schedule of relevant Milestones

Milestone number [59]	Milestone name	Lead beneficiary number	Delivery date from Annex I [60]	Comments
MS7	Open-House Fairs at NOPTILUS Test Case	2	48	Successful completion of fairs

Project Number [1]	270180	Project Acronym [2]	NOPTILUS

List and Schedule of Milestones

Milestone number [59]	Milestone name	WP number [53]	Lead beneficiary number	Delivery date from Annex I [60]	Comments
MS1	System Specification Complete	WP2	7	6	D2.1 Ready
MS2	Communications, vision and sonar-based mapping work as intended	WP3	5	30	Successful completion of real-life tests ruring Integration Week 2 and successful completion of the simulation-based evaluation
MS3	Localization, collaborative sensing, and fused vision/sonar work fully-functional, mounted on AUV	WP3	5	30	Tests during Integration Week 2, successful according to D8.1.
MS4	Cooperative mapping and control modules work fully-functional, mounted on AUV systems	WP7	1	42	Tests during Integration Week 3, successful according to D8.1.
MS5	Successful operation/ communication of all NOPTILUS hardware/software components	WP8	7	43	Successful operation of the overall NOPTILUS system during Demonstrations according to D8.1
MS6	Successful finalization of demonstrations	WP8	1	48	Successful completion of Demonstrations according to D8.1
MS7	Open-House Fairs at NOPTILUS Test Case	WP9	2	48	Successful completion of fairs

WT5:
Tentative schedule of Project Reviews

Project Number [1]	270180	Project Acronym [2]	NOPTILUS

Tentative schedule of Project Reviews			
Review number [65]	Tentative timing	Planned venue of review	Comments, if any

WT6:
Project Effort by Beneficiary and Work Package

Project Number [1]	270180	Project Acronym [2]	NOPTILUS

Indicative efforts (man-months) per Beneficiary per Work Package

Beneficiary number and short-name	WP 1	WP 2	WP 3	WP 4	WP 5	WP 6	WP 7	WP 8	WP 9	Total per Beneficiary
1 - CERTH	1.00	1.00	1.00	30.00	10.90	3.00	38.00	14.00	3.00	101.90
2 - FEUP	4.00	25.00	8.00	10.00	6.00	2.00	9.00	44.00	6.00	114.00
3 - ETH Zurich	0.00	0.00	0.00	0.00	14.40	0.00	0.00	0.00	0.00	14.40
4 - TU Delft	2.00	4.00	15.00	0.00	0.00	0.00	4.00	5.00	3.00	33.00
5 - TSI	2.00	3.00	18.00	13.00	0.00	29.00	8.00	9.00	5.00	87.00
6 - Imperial	0.00	5.00	22.00	12.00	1.00	3.00	3.00	8.00	3.00	57.00
7 - MST	4.00	28.00	11.00	0.00	6.00	4.00	6.00	57.00	6.00	122.00
8 - APDL	2.00	9.00	0.00	0.00	0.00	0.00	0.00	26.00	3.00	40.00
9 - CNRS	4.00	0.00	1.00	1.00	14.00	0.00	0.00	4.00	3.00	27.00
Total	19.00	75.00	76.00	66.00	52.30	41.00	68.00	167.00	32.00	596.30

WT7:
Project Effort by Activity type per Beneficiary

Project Number [1]	270180	Project Acronym [2]	NOPTILUS

Indicative efforts per Activity Type per Beneficiary

Activity type	Part. 1 CERTH	Part. 2 FEUP	Part. 3 ETH Zur	Part. 4 TU Delf	Part. 5 TSI	Part. 6 Imperia	Part. 7 MST	Part. 8 APDL	Part. 9 CNRS	Total
1. RTD/Innovation activities										
WP 2	1.00	25.00	0.00	4.00	3.00	5.00	28.00	9.00	0.00	75.00
WP 3	1.00	8.00	0.00	15.00	18.00	22.00	11.00	0.00	1.00	76.00
WP 4	30.00	10.00	0.00	0.00	13.00	12.00	0.00	0.00	1.00	66.00
WP 5	10.90	6.00	14.40	0.00	0.00	1.00	6.00	0.00	14.00	52.30
WP 6	3.00	2.00	0.00	0.00	29.00	3.00	4.00	0.00	0.00	41.00
WP 7	38.00	9.00	0.00	4.00	8.00	3.00	6.00	0.00	0.00	68.00
WP 8	14.00	44.00	0.00	5.00	9.00	8.00	57.00	26.00	4.00	167.00
Total Research	97.90	104.00	14.40	28.00	80.00	54.00	112.00	35.00	20.00	545.30
2. Demonstration activities										
Total Demo	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3. Consortium Management activities										
WP 1	1.00	4.00	0.00	2.00	2.00	0.00	4.00	2.00	4.00	19.00
WP 9	3.00	6.00	0.00	3.00	5.00	3.00	6.00	3.00	3.00	32.00
Total Management	4.00	10.00	0.00	5.00	7.00	3.00	10.00	5.00	7.00	51.00
4. Other activities										
Total other	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	101.90	114.00	14.40	33.00	87.00	57.00	122.00	40.00	27.00	596.30

WT8:
Project Effort and costs

Project Number [1]	270180	Project Acronym [2]	NOPTILUS

Project efforts and costs

Beneficiary number	Beneficiary short name	Estimated eligible costs (whole duration of the project)						Requested EU contribution (€)
		Effort (PM)	Personnel costs (€)	Subcontracting (€)	Other Direct costs (€)	Indirect costs OR lump sum, flat-rate or scale-of-unit (€)	Total costs	
1	CERTH	101.90	478,904.00	1,500.00	75,305.00	383,123.00	938,832.00	716,960.00
2	FEUP	114.00	399,000.00	1,500.00	174,175.00	343,905.00	918,580.00	708,910.00
3 (TERMINATED)	ETH Zurich	14.40	89,808.00	0.00	1,831.00	54,983.00	146,622.00	109,966.00
4	TU Delft	33.00	157,047.00	0.00	33,000.00	180,777.00	370,824.00	293,914.00
5	TSI	87.00	348,000.00	1,500.00	63,200.00	246,720.00	659,420.00	512,540.00
6	Imperial	57.00	289,805.00	2,500.00	70,500.00	216,182.00	578,987.00	447,366.00
7	MST	122.00	288,042.00	1,500.00	70,000.00	214,825.00	574,367.00	446,194.00
8	APDL	40.00	261,200.00	0.00	110,500.00	74,340.00	446,040.00	246,210.00
9	CNRS	27.00	161,457.00	0.00	67,800.00	137,553.00	366,810.00	297,651.00
Total		596.30	2,473,263.00	8,500.00	666,311.00	1,852,408.00	5,000,482.00	3,779,711.00

1. Project number

The project number has been assigned by the Commission as the unique identifier for your project. It cannot be changed. The project number **should appear on each page of the grant agreement preparation documents (part A and part B)** to prevent errors during its handling.

2. Project acronym

Use the project acronym as given in the submitted proposal. It cannot be changed unless agreed so during the negotiations. The same acronym **should appear on each page of the grant agreement preparation documents (part A and part B)** to prevent errors during its handling.

53. Work Package number

Work package number: WP1, WP2, WP3, ..., WPn

54. Type of activity

For all FP7 projects each work package must relate to one (and only one) of the following possible types of activity (only if applicable for the chosen funding scheme – must correspond to the GPF Form Ax.v):

• **RTD/INNO =** Research and technological development including scientific coordination - applicable for Collaborative Projects and Networks of Excellence

• **DEM =** Demonstration - applicable for collaborative projects and Research for the Benefit of Specific Groups

• **MGT =** Management of the consortium - applicable for all funding schemes

• **OTHER =** Other specific activities, applicable for all funding schemes

• **COORD =** Coordination activities – applicable only for CAs

• **SUPP =** Support activities – applicable only for SAs

55. Lead beneficiary number

Number of the beneficiary leading the work in this work package.

56. Person-months per work package

The total number of person-months allocated to each work package.

57. Start month

Relative start date for the work in the specific work packages, month 1 marking the start date of the project, and all other start dates being relative to this start date.

58. End month

Relative end date, month 1 marking the start date of the project, and all end dates being relative to this start date.

59. Milestone number

Milestone number:MS1, MS2, …, MSn

60. Delivery date for Milestone

Month in which the milestone will be achieved. Month 1 marking the start date of the project, and all delivery dates being relative to this start date.

61. Deliverable number

Deliverable numbers in order of delivery dates: D1 – Dn

62. Nature

Please indicate the nature of the deliverable using one of the following codes

R = Report, **P** = Prototype, **D** = Demonstrator, **O** = Other

63. Dissemination level

Please indicate the dissemination level using one of the following codes:

• **PU =** Public

• **PP =** Restricted to other programme participants (including the Commission Services)

• **RE =** Restricted to a group specified by the consortium (including the Commission Services)

• **CO =** Confidential, only for members of the consortium (including the Commission Services)

• **Restreint UE =** Classified with the classification level "Restreint UE" according to Commission Decision 2001/844 and amendments

• **Confidentiel UE =** Classified with the mention of the classification level "Confidentiel UE" according to Commission Decision 2001/844 and amendments

• **Secret UE =** Classified with the mention of the classification level "Secret UE" according to Commission Decision 2001/844 and amendments

64. Delivery date for Deliverable

Month in which the deliverables will be available. Month 1 marking the start date of the project, and all delivery dates being relative to this start date

65. Review number

Review number: RV1, RV2, ..., RVn

66. Tentative timing of reviews

Month after which the review will take place. Month 1 marking the start date of the project, and all delivery dates being relative to this start date.

67. Person-months per Deliverable

The total number of person-month allocated to each deliverable.

SEVENTH FRAMEWORK PROGRAMME

THEME 3

"Information and Communication Technologies"

Grant agreement for: LARGE-SCALE INTEGRATING PROJECT (IP)

Annex I - "Description of Work"

AUTONOMOUS, SELF-LEARNING, OPTIMAL AND COMPLETE UNDERWATER SYSTEMS

NOPTILUS

Work programme topic addressed

FP7-ICT-2009.2.1: COGNITIVE SYSTEMS AND ROBOTICS

C. NEW WAYS OF DESIGNING AND IMPLEMENTING COMPLETE ROBOTIC SYSTEMS

Grant agreement no: 270180
Date of preparation of Annex I (latest version): 2013-15-3

List of Participants

PARTICIPANT NO.	PARTICIPANT ORGANISATION NAME	PARTICIPANT SHORT NAME	COUNTRY
1	Centre for Research and Technology – Hellas	CERTH	GR
2	Faculdade de Engenharia da Universidade do Porto	FEUP	PT
3 (Deleted)	Eidgenössische Technische Hochschule Zürich	ETH Zurich	CH
4	Delft University of Technology	TU Delft	NL
5	Telecommunication Systems Institute	TSI	GR
6	Imperial College	Imperial	UK
7	OceanScan - Marine Systems & Technology, Lda	MST	PT
8	Administração dos Portos do Douro e Leixões, SA	APDL	PT
9	Centre National de la Recherche Scientifique (CNRS)	CNRS	FR

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List of Abbreviations

ASV	Autonomous surface vehicle
AUV	Autonomous underwater vehicle
C-MAC	Cognitive Medium Access Control
CAO	Cognitive-based Adaptive Optimization
CDMA	Code-Division Multiple Access
CSMA	Carrier Sense Medium Access
CTD	Conductivity, temperature and depth
FDMA	Frequency-Division Multiple Access
FSK	Frequency-Shift Keying
GP	Gaussian Process
GPS	Global positioning system
GSM	Global system for mobile communications
ICI	Inter Carrier Interference
IMU	Inertial Measurement Unit
MAC	Medium Access Control
MDS	Multi-Dimensional Scaling
MIMO	Multi-Input Multi-Output
PAN	(multi-AUV) Planning, Assignment and Navigation
PCFG	Probabilistic Context-free Grammars
RIPT	Receiver-Initiated Packet Train
ROV	Remotely operated vehicle
S-INS	Sonar-aided Inertial Navigation Systems
SLAM	Simultaneous Localization And Mapping
TDMA	Time-Division Multiple Access
UAV	Unmanned air vehicle
UUV	Unmanned underwater vehicle

B1. CONCEPT AND OBJECTIVES, PROGRESS BEYOND STATE-OF-THE-ART, S/T METHODOLOGY AND WORK PLAN

B1.1 Concept and project objectives

B1.1.1 MOTIVATION AND OBJECTIVES

Despite the impressive methodological and technological advances in the field of underwater robotics in recent years, the existing approaches are far from being able to design and deploy teams of Autonomous Underwater Vehicles (AUVs) that can *fully autonomously* take over *real-life complex situation awareness operations* such as environmental monitoring and clean-up operations, seafloor mapping, security and surveillance, inspection of underwater structures, etc. In the majority of such applications, ROVs (Remotely-operated Underwater Vehicles) are employed, where human operators are called to (a) “assess and understand” the ROV’s surrounding environment via the information received by the vehicles’ sensors and (b) remotely navigate the vehicles in an attempt to accomplish the particular mission the vehicles are deployed for. The involvement of human operators is very costly, as it requires well-trained and highly-experienced personnel for long periods of time, and, in most cases, it renders the deployment of *cooperative systems* of underwater vehicles infeasible as it is practically impossible for the operators to concurrently monitor/navigate the ROVs and coordinate with other operators.

Very recently there has been an intensive research and development effort towards designing and deploying teams of cooperative AUVs that overcome the above-mentioned shortcomings of humanly-operated ROVs: various R&D projects (including the FP6 ICT projects GREX and VENUS and the FP7 ICT projects Co3-AUVs, TRIDENT, C4C and SHOAL) have developed or are developing new methodologies and designs for multi-AUV[1] coordination and cooperative control. These projects seek to develop efficient algorithms for AUVs operating under severe environmental conditions (e.g. in the presence of strong currents and turbulences). Moreover, they need to deal with the poor communication, sensing, and localization capabilities of underwater vehicles which mainly rely on sonars both for communications and sensing, while navigating in GPS-denied or GPS-limited environments. Very impressive test cases have been (or will be) demonstrated as parts of the aforementioned R&D projects, with teams of AUVs being able to perform – cooperatively – formation control, path planning and target tracking, seafloor exploration and environmental monitoring, underwater object manipulation, etc.

However, despite the advances made through current multi-AUV R&D endeavors, *the existing or planned multi-AUV systems are far from being capable of fully autonomously* taking over real-life complex situation-awareness operations. Such operations require that the overall system is “equipped” with reasoning, situation understanding, planning, and decision-making abilities – attributes that existing/planned designs are unable to provide. Instead, current designs have to heavily rely on *human operators* who assign a set of high-level tasks to the AUVs (e.g. a specific set of locations or paths/targets the AUVs have to visit or follow, respectively). As soon as the high-level tasks have been assigned, the existing/planned designs focus on accomplishing them successfully while taking into account constraints and requirements, such as obstacle-avoidance, energy-consumption, minimum formation error, etc.

[1] It is worth noticing that, in most cases, the team of vehicles involves also cooperation of the AUVs with surface units such as Autonomous Surface Vehicles (ASV) or surface buoys used for monitoring the overall AUV team and/or improving the localization capabilities of the AUVs.

As such, existing/planned designs do not provide integrated AUV systems that are able to (a) *automatically assess and understand* the current situation (with regards to the particular mission the AUVs have been deployed for) and (b) *autonomously assign tasks/navigate the AUVs* so that the overall system accomplishes successfully and fully autonomously the desired mission. Even worse, and mostly due to the involvement of human operators, existing approaches do not provide any guarantees that the overall multi-AUV mission will be accomplished optimally (or, at least, nearly-optimally). Instead, there exist many cases where operator-made decisions are not just far from being optimal but they may even put the success of the overall mission at stake.

To better appreciate the significance and need for *an autonomous multi-AUV system able to (a) automatically assess and understand the underwater environment and (b) autonomously and nearly-optimally assign/navigate the AUVs,* consider the scenario where a multi-AUV system is deployed to prevent an ecological disaster due to the sinking of a ship carrying liquid chemicals. During such a critical mission, there is an urgent need to perform – as accurately and as fast as possible – the following *distributed estimation, recognition and situation understanding* tasks: (a) locate the shipwreck and inspect its damaged compartments, (b) map the area around the shipwreck and determine the ship's stability, (c) determine the locations where chemicals are leaking from and (d) monitor (i.e. locate and track) the spread of the chemicals in the water. Accomplishing all these tasks accurately and in a timely manner is necessary in order to decide whether nearby coastal areas need to be evacuated, when chemical neutralizers need to be spread and over which area, whether the tanks need to be permanently or temporarily sealed, and whether it's best to hoist up the sunken ship or pump the content of its leaking tanks into other vessels.

When using existing/planned multi-AUV designs and approaches, most of the critical – for the success of the overall operation – high-level tasks in the above scenario will have to be performed by human operators: they will have to determine the stability of the shipwreck, detect the damaged/leaked areas on the ship, and identify/track/predict the movement and spread of the chemical spill. Most importantly, the human operators will have to decide, in real-time, the locations the AUVs will need to inspect and to assign different tasks to each AUV (e.g. some of the AUVs may be assigned shipwreck-exploration tasks while others may be used for identifying/tracking the spread of the chemical spill).

There are two main issues of concern when human operators are employed to perform high-level monitoring and control, as these described above:

1. Human operators must be able to *detect, recognize and predict* not just static features but also dynamic processes (e.g. the shipwreck movement and dynamic stability, the locations where chemicals are leaking from, the dynamics of the chemicals' spread, etc). However, as the human-operators have to rely on the limited, communication, sensing, and localization capabilities of the AUVs (based primarily on sonar sensors), detecting, recognizing and predicting static as well as dynamic features is an extremely difficult task for them. As a result, the possibility of miscalculating or inaccurately estimating/predicting features and spatio-temporal processes of interest is extremely high and may lead to situations in which, e.g., the operator does not identify a major leak from the shipwreck, or loses track of the chemical spill, or underestimates its spread with catastrophic consequences.
2. Most importantly, the human operators must very *carefully and efficiently assign* the AUVs to different tasks and areas based on their capabilities and mission requirements. As the AUV assignment has to be performed dynamically and in real-time, the operators may "send" the AUVs to areas where no or little information is available, while leaving areas of high importance "unattended". Precious time for the overall mission may be wasted in such event, which may

put its success at risk. Note that even for a small number of AUVs, the number of real-time decisions (assignments) that must be made by the operators in short time is quite high and so is the possibility of making erroneous decisions.

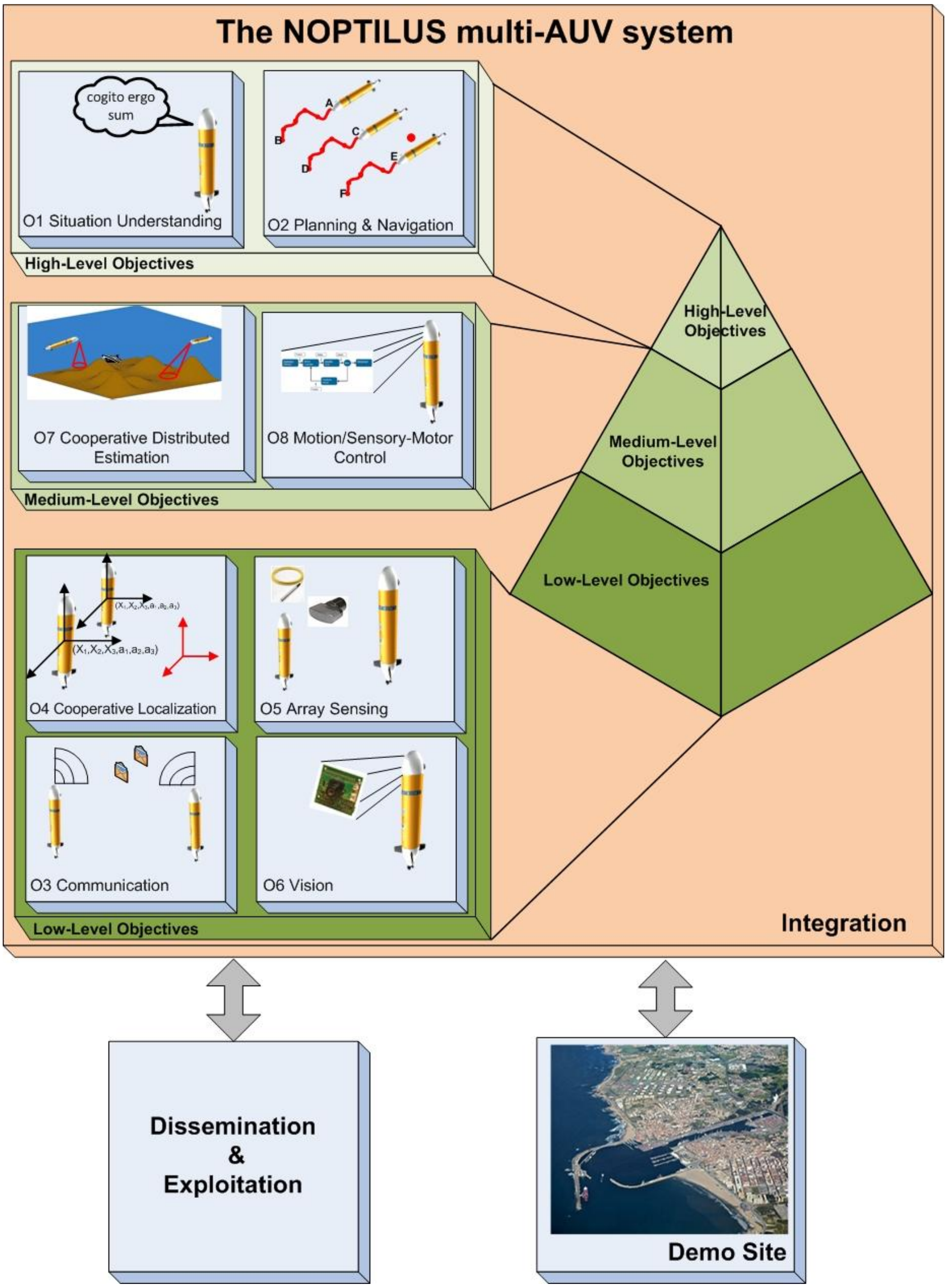


Figure 1: Schematic of the NOPTILUS Project

Motivated by – but not limited to – the above scenario, NOPTILUS's main objective is to introduce, develop, test, and evaluate a new fully-autonomous multi-AUV concept/system that seeks to overcome the above-mentioned shortcomings, by replacing the human-operator high-level monitoring and navigation by a fully-autonomous one. To achieve this goal, this proposal will focus mainly on the development of fully-automated techniques and designs that will render the

NOPTILUS overall system capable of achieving the two High-Level Objectives (related to the shortcomings described above) listed in the following Table.

Table 1. NOPTILUS <u>High-Level Objectives</u> towards the development of Fully-Autonomous, Complete Systems of AUVs
Advance the current state-of-the art and provide all necessary methodological and algorithmic tools for the development of designs capable of
(O1) *Automatically detecting, recognizing, understanding and predicting static underwater features and patterns as well as highly dynamic phenomena and events* taking place and influencing the underwater operations. ***NOPTILUS Approach to address the Key Objective:*** Machine-learning and reinforcement-learning tools, and probabilistic context-free grammars will be exploited in innovative ways and combined with a rich set of experimental observation logs from human-operated underwater missions, to develop a cognitive-based "Learning from past missions" and structured prediction designs capable of successfully addressing objective (O1).
(O2) Providing *arbitrarily-close-to-the-optimal*[2]*, real-time, scalable, cooperative, and distributed, fully-autonomous multi-AUV Planning, Assignment and Navigation (PAN).* Here, the term <u>optimal multi-AUV PAN</u> refers to the AUV <u>motion strategy</u> which – given the physical, communication, computation, etc system constraints and limitations and – by making optimal use of the available energy, communication, and computational recourses; • maximizes the acquired information and accuracy of the particular distributed estimation, recognition and situation understanding task(s) the NOPTILUS system has been deployed for and • minimizes the time and processing required for accomplishing the aforementioned estimation, recognition and situation understanding task(s). ***NOPTILUS Approach to address the Key Objective:*** A recently developed strategy that combines Cognitive-based Adaptive Optimization (CAO) together with a convex decision-making motion design tool that can provide scalable, robust and arbitrarily-close-to-the-optimal[3] performance will be further enhanced, updated and revised so as to meet the requirements of this objective.

The above two main objectives of NOPTILUS are crucial and necessary but not sufficient for the development of a fully-autonomous and complete multi-AUV system. Groundbreaking innovations and advances beyond the current state-of-the-art are also required in several more components and technologies involved in multi-AUV systems, so as to successfully address the challenges associated with operation in an underwater environment and lead to an *integrated* multi-AUV system capable of fully autonomously, as well as robustly and dependably, perform real-life complex situation-awareness operations. Within NOPTILUS, we have identified these main additional advances – beyond the current state-of-the-art and complementary to objectives (O1)

[2] Throughout this proposal the terms "nearly-optimal" and "arbitrarily-close-to-the-optimal" will be used interchangeably as the NOPTILUS system provides in real-time and automatically the AUV motion strategies that result in a system performance that is <u>as close to the optimal one as desired without sacrificing scalability</u>.

[3] Note that contrary to traditional multi-robot motion strategy designs, where the goal is to design, on-line, AUVs trajectories that maximize the *estimation accuracy* of a particular situation awareness operation (e.g. the precisions of the constructed map), in the case of NOPTILUS the *more complex and general objective of optimizing the information acquisition for the estimation, as well as recognition and situation understanding tasks,* is addressed.

and (O2) – necessary in order to develop a fully autonomous multi-AUV system. These advances are listed as a set of low-level and medium-level objectives in the following Table:

Table 2. NOPTILUS Low-level and Medium-level Objectives towards the development of Fully-Autonomous, Complete Systems of AUVs
Low-level NOPTILUS objectives: Innovations are required to provide significantly higher accuracy and reliability in communication, sensing, and localization techniques and systems.
(O3) The poor performance of existing sonar-based underwater communication systems limits severely the capabilities of multi-AUV systems especially when deployed in situation-awareness operations. Radically new approaches are necessary for realizing advanced sonar-based multi-AUV communication systems that will provide significantly higher throughput and reliability. ***NOPTILUS Approach to address the Key Objective:*** A novel *multi-carrier underwater acoustic communication system* will be designed and deployed within NOPTILUS system to significantly improve the performance and reliability of AUV communications as compared to existing systems. This will become possible by introducing novel techniques to model, control, and exploit channels that contain propagation paths with different Doppler shifts. In particular, a Cognitive Medium Access Control (C-MAC) layer will be developed to allow for co-existence of multiple communication links. Every link will sense the propagation environment and adapt its transmission accordingly using power/bit loading of the different carriers active in the multicarrier system. *Cooperation* among neighboring nodes will also be studied to further increase the overall throughput and reliability of the communications network. This way, the AUVs will act as a team with distributed communication capabilities, capable of achieving operational objectives more efficiently.
(O4) One of the main barriers in the deployment of multi-AUV systems for situation awareness, is poor localization. To address this limitation, key innovations are necessary in the form of new and advanced designs and techniques that will significantly improve the positioning capabilities of multi-AUV systems. ***NOPTILUS Approach to address the Key Objective:*** Special focus will be given within NOPTILUS towards the design and deployment of a high-efficiency, *distributed, and cooperative AUV localization system*. This system will exploit and combine complementary concepts and designs such as Multi-Dimensional Scaling (MDS), multi-path and path loss models, signal fusion, AUV re-surfacing, and information-driven coordinated swarm motion.
(O5) In addition to sonar-based communication systems, fundamentally different approaches are necessary in order to introduce novel sonar-based multi-AUV sensing systems whose accuracy and reliability significantly outperforms existing systems. ***NOPTILUS Approach to address the Key Objective:*** *Collaborative sensing using MIMO (Multi-Input, Multi-Output) sonar,* where the sonar measurements from different AUVs are intelligently combined, will be developed and utilized in NOPTILUS to endow the NOPTILUS system with high-accuracy and high-resolution sensing capabilities. Motion locking, orthogonal code design for different sonars, and cognitive sonar techniques will be exploited towards this objective.
(O6) Due to poor underwater visibility and lighting conditions as well as weight, volume, power and cost considerations, underwater vision systems have had very limited applicability so far. Instead, most current underwater vehicles rely solely on sonar sensors. However, underwater vision systems can significantly enhance the capabilities and extend the operation range of autonomous multi-AUV systems especially in situations where sonar measurements are extremely poor (e.g. in distances less than 5m), or when the required information cannot be provided by sonars (e.g. albedo). Moreover, fusion across space and time of sonar and visual measurements can significantly improve situation awareness by providing an information-rich representation of the AUVs environment. This in effect will increase the probability of correct classification, obstacle detection, etc, and thus improve the

efficiency and reliability of the multi-AUV system.

NOPTILUS Approach to address the Key Objective: Advanced but low-cost *"seeing through murky waters" vision systems* will be designed, based on photometric stereo for determining the – unknown – underwater objects' albedo and shape. This will be achieved by precisely modeling the light scattering caused by debris and large molecules floating in the water (e.g. plankton). Moreover, shape information extracted from photometric stereo will be combined *(fused)* with sonar information, while taking into account the type and amount of information available in each measurement.

Medium-Level NOPTILUS objectives: To leverage the communication, localization, and sensing methodologies and techniques, which will be developed within NOPTILUS for addressing the low-level objectives (O3)-(O6), in order to introduce new advanced algorithms and designs that will support highly accurate and robust map construction, process tracking, and path following of multi-AUV teams.

(O7) In order to provide efficient and accurate situation and process understanding during situation-awareness operations multi-AUV systems must be able to construct accurate 3D maps of the area under surveillance and accurately locate and track dynamic phenomena of interest (e.g. movement and spread of chemical spills).

NOPTILUS Approach to address the Key Objective: Advanced and highly-accurate *cooperative and distributed estimation algorithms* will be developed for constructing *static and dynamic 3D maps of the benthic environment, as well as for estimating and tracking dynamically-evolving processes,* such as the spread of hazardous chemicals in water. Machine learning approaches (e.g. using Gaussian Processes) to spatio-temporal process modeling, dimensionality reduction and quantization techniques for sensor data communication and fusion will be appropriately extended and adapted to the time and resolution varying requirements of the task undertaken by the AUV team. Moreover, the information content, classification and localization utility of sensor observations will be considered when designing estimation algorithms that adhere to strict communication and processing constraints of AUVs.

(O8) A prerequisite for efficient and nearly-optimal AUV PAN – see objective (O2) – is that each single AUV is able to accurately follow and track the assignment and navigation commands as provided by the NOPTILUS PAN module. There are two important practical problems regarding this issue:

1. strong currents, turbulences, etc may force the AUV to significantly deviate from the assigned trajectory, which may hinder meeting the mission's objectives, or even lead to catastrophic events, such as collisions with obstacles or other AUVs.
2. in cases where the global localization accuracy becomes very poor (e.g. when no external positioning measurements or aids are available for extended periods of time), the AUVs may not be able to perform state-space trajectory following.

NOPTILUS Approach to address the Key Objective

1. A recently developed *learning-based strategy* by one of NOPTILUS partners – capable of providing robust performance while being arbitrarily close to the optimal – *will be appropriately combined* within NOPTILUS with *existing robust, nonlinear (but non-adaptive) motion control* techniques.
2. In case of poor or unavailable global localization, the NOPTILUS system will *switch to sensory-motor control*, with the AUV performing perceptual tracking of a trajectory described as a (sparse) sequence of observations perceived by the AUV's on-board sensors. A recently developed sensory-motor approach by one of NOPTILUS partners – successfully implemented and tested in terrestrial robots – will be appropriately extended and adapted within NOPTILUS to take into account the presence of currents and turbulences, as well as the limited sensing capabilities of the AUVs (as compared to those of ground vehicles).
3. A *switching mechanism* will be developed for appropriately activating/deactivating the motion control or the sensory-motor control module. Moreover, since disturbances in the AUVs' motion (e.g. due to currents, turbulences or, even, the switching mechanism) may increase the probability of collisions, a collision-avoidance controller will be designed which will be activated whenever the AUV approaches an obstacle, the sea-floor, or

other AUVs beyond a safety margin determined by the operating conditions and dynamics of the vehicle.

Remark: It is worth noticing that all the above objectives apply also in the case where the AUV team is cooperating with surface units such as ASVs, buoys, etc. Throughout this proposal and in order to avoid unnecessary text duplication, the terms “multi-AUV” or “team of AUVs” should be understood as systems of AUVs that are possibly cooperating with surface units.

In order to better understand the meaning and importance of NOPTILUS objectives (O1)-(O8) with respect to real-life missions, we provide in the next table a brief description of **“what”** – a completely autonomous multi-AUV system that successfully addresses (O1)-(O8) – **“would be able to do”** in case it was deployed in a real-life mission like the one described in the beginning of this section.

Table 3. A system successfully addressing (O1)-(O8) in case of a mission involving the sinking of a ship carrying liquid chemicals, should be able to		
(O1)	Situation Understanding	perform with accuracy the following tasks: (a) understand and recognize the particular situation the accident is at (e.g. whether the ship is currently sinking or it has stabilized on the seafloor, whether and where there is a chemical leak on the ship, whether the chemicals has started spreading, etc); (b) detect faulty or unusual multi-AUV system behavior and understand what is happening (e.g. AUV got caught on a fishing net, strong currents prevent the AUVs from entering an area, etc);
(O2)	Planning, Assignment & Navigation	design – in real-time – the AUVs trajectories with no human intervention so that the overall mission is accomplished on time and the information generated by the system – see objectives (O1) and (O7) – is provided at the desired accuracy;
(O3)	Underwater Communications	provide with highly more reliable acoustic communications than existing underwater communication systems;
(O4)	Underwater Localization	achieve to keep all AUVs accurately localized whenever the trajectory generator – objective (O1) – requests so. Please note that AUVs are always required to be localized unless the trajectory generator decides to switch to sensory-motor control, e.g. in case where it decides that it would be more effective to first have the AUVs “come close to the shipwreck” and then localize themselves using resurfacing;
(O5)	Underwater Sensing	provide with highly more accurate static and dynamic sensing information than existing underwater sonar or vision sensing systems;
(O6)	Underwater Vision and Fusion	be able to “see” crucial information (e.g. that there is a whole in the shipwreck leaking chemicals) that existing underwater sonar and vision systems are not able to “see”;

(O7)	Estimation for Map Construction & Process Tracking	perform with high accuracy the following tasks: (a) locate and track the location of the ship while it is sinking; (b) locate the exact location of the ship when it stabilized on the seafloor; (c) construct a map of the seafloor area around the shipwreck; (d) track the chemical spill;
(O8)	Motion and Sensory-Motor Control	(a) provide with highly more efficient trajectory following control systems than existing ones especially in cases of strong currents and turbulences; (b) in cases where the trajectory generator – objective (O1) – decides that localization can be lost, efficiently achieve to guide the AUVs to e.g. surround the shipwreck with each AUV being within given distances from the shipwreck and the rest of the team.

B1.1.2 NOPTILUS S&T OBJECTIVES

Based on the concise analysis presented above, NOPTILUS seeks to address a number of fundamental methodological, technological, and practical challenges and thus lead to the development of a generic fully-functional multi-AUV system (shown in Figure 1) capable of providing fully-autonomous, robust and dependable, as-close-to-optimal-as-desired performance in a variety of *real-life* complex situation-awareness operations. This major objective is pursued within NOPTILUS via a number of multifaceted actions and S&T Objectives:

ST1. Advance the current state-of-the-art to develop the scientific basis, methodologies and algorithms that **successfully and efficiently address all low-, medium- and high-level objectives (O1)-(O8)** described in the previous section. All methodologies and algorithmic developments should be **fully-scalable** so that they can be realized even when large teams of AUVs are deployed and, moreover, they should be **implementable using existing low-cost, off-the-shelf technologies**. Additionally, they should take into consideration and fully obey **all physical, communication, processing, and resource constraints** induced by the particular underwater application the NOPTILUS system is deployed in.

ST2. Specify in detail all the NOPTILUS system **hardware components** (e.g. sensors, acoustic modems, vision systems, on-board processors, etc) so that the above-mentioned algorithmic developments can be easily implemented on NOPTILUS AUVs at **low cost, minimum energy and weight constraints but without sacrificing efficiency or robustness**.

ST3. **Interface and integrate** all the above-mentioned methodologies, algorithms and components into a **complete, fully-autonomous, multi-AUV monitoring and control system** capable of: (a) automatic situation understanding and (b) autonomously assigning tasks/navigating the AUVs so that the overall system accomplishes **nearly-optimal, complex, real-life situation-awareness operations** such as environmental monitoring and clean-up operations, seafloor mapping, security and surveillance, inspection of underwater structures, etc.

ST4. **Implement and demonstrate** the complete NOPTILUS system on a **24hours/7days-a-week** application in the Port of Leixões (Portugal) concerning a multi-task, underwater persistent data collection either on a regular basis or on-demand.

ST5. **Evaluate** the performance of the overall NOPTILUS system with emphasis on its robustness, dependability, adaptability, and flexibility - especially when it deals with

completely unknown underwater environments and situations "never taught before" - as well as its ability to provide **arbitrarily-close-to-the-optimal** performance.

Finally, within NOPTILUS all necessary measures will be taken so that the NOPTILUS advances are **disseminated and exploited** to the full extend, with focus on the robotic-related R&D community but also on the potential users of the NOPTILUS system in Europe and worldwide. Also, of special focus within NOPTILUS is its **training** activities targeted not only to researchers but also to potential users of the system.

B1.1.3 Relevance to the Topics addressed in this Call

NOPTILUS directly addresses many of the topics mentioned in FP7-ICT-2009.2.1: Cognitive Systems and Robotics of the ICT EU program and, particularly, in target outcome c. New Ways of Designing and Implemented Complete Robotic Systems. The following table summarizes the relevance of the NOPTILUS approach to the topics addressed in the Call.

Table 4. Relevance of NOPTILUS to the Topics addressed in the Call

Topic	Relevance of NOPTILUS
Engineering systems with the capability to sense and understand an unstructured environment …	One of the 2 key objectives of NOPTILUS – see objective (O1) in section B1.1.1 – is the development of an underwater multi-AUV system capable of sensing and understanding fully-autonomously totally unstructured underwater environments (no prior knowledge is assumed about the underwater environment within which the NOPTILUS system is deployed).
systems should be … ***robust*** …; ***adaptive***; *more effective…* because they can predict; *more natural:* …; tolerant to the ambiguity and **uncertainty.**	Robustness, adaptability, predictability and tolerance to ambiguity and uncertainty are fundamental ingredients in all of the NOPTILUS components and modules.
System capabilities in dimensions such as deliberation and learning, and innovation and creativity, would appear to be necessary to meet this aim. … For the purposes of this work programme a **cognitive system** …	Cognition, perception and learning appears and is of crucial importance at all levels and modules of the NOPTILUS system: from cognitive-based communications and sonars (lower-level systems) via GP-based estimation and perceptual sensory-motor control and learning motion control (medium level) to – high level – learning and cognitive-based situation understanding and motion strategy modules.
New ways of designing and implementing complete robotic systems that operate largely autonomously in loosely structured dynamic environments …	This is actually the main promise of NOPTILUS: to design and demonstrate on a 24hours/7days-a-week basis, the first fully autonomous underwater vehicle system operating in a highly unstructured and totally unknown environment.
Systems may be distributed and should integrate rich **sensory-motor** skills …	Requiring for an underwater multi-vehicle system to be fully autonomous is not possible if it does not have the ability to perform sensory-motor control at certain circumstances. NOPTILUS will provide sensory-motor control in a more challenging and complicated manner than that of existing (vision-based) sensory-motor control designs for ground or air robots as it will have to rely mainly on sonar measurements.
Research and development pertaining to targets (a), (b), (c) and (d) will be guided by demanding, yet pragmatic, application scenarios.	NOPTILUS system will be demonstrated on a real-life application and on a 24hours/7days-a-week basis, where it will take over many different operations accomplished currently

	by humans or human-operated ROVs.

B1.1.4 THE NOPTILUS TEST CASE/SCENARIOS

The NOPTILUS test case is intended to exercise, test, evaluate, and demonstrate, in a realistic environment, the Port of Leixões, the novel algorithms, tools, and technologies developed in this project.

Location

The location of the Test Case of NOPTILUS is the Port of Leixões which comprises the largest seaport infrastructure in the North of Portugal and one of the most important in the country. With 5 km of quays, 55 hectares of embankments and 120 hectares of wet area, Leixões has excellent road, rail and maritime access and is equipped with advanced information systems for vessel traffic control and management. Representing 25% of the Portuguese foreign trade and handling 15 million tons of commodities a year, the Port of Leixões is one of the most competitive and versatile multi-purpose ports in the country. Benefiting from a strategic location with a hinterland rich in industry and commerce, the Port of Leixões has a privileged position in the context of the European port system. It operates 365 days a year with high productivity levels and with low vessel-turnaround time at the quays. Recent investments in the port facilities and in the navigation channel made it possible for the Port of Leixões to receive Panamax type ships. A new cruise terminal, due to open in 2010, will complete a major modernization of this port.

Sustainable development is a key component of the Strategic Plan of the Port of Leixões. This is even more important because of the urban surroundings. New challenges arise from the selective collection of waste, environmental and structural inspections, minimization of the environmental impact deriving from commodity handling, environmental certification, cleaning of the wharf area of the port, leveling of the final stretch of the River Leça, monitoring security threats, monitoring of the navigation channel and development of advanced capabilities for intervention in the case of disasters.

Existing Infrastructure

Existing AUV/ASV-infrastructure, owned by FEUP, will be appropriately upgraded and integrated for the purposes of NOPTILUS demonstrations. The figure below presents some examples of the AUV/ASV-infrastructure to be used by NOPTILUS.

Pilot's boa

Tug boat

Support vessel

The **IES ROV** is a modified Phantom 500 ROV model from Deep Ocean Engineering. The innovations include on-board power and computer systems (to minimize the number of wires in the tether cable), tele-operation and tele-programming modes and an integrated navigation system which fuses data from an external acoustic system and internal navigation sensors. The inspection package includes a video camera (Inspector, zoom 12:1) mounted on a pan and tilt unit (Imenco) with 600W of light (DSP\&L). The navigation package includes a Doppler Velocity Log (Argonaut/Sontek), an Inertial Unit (HG1700 /Honeywell), a Digital Compass (TCM2/PNI) and acoustic beacons (20-30KHz).

The **KOS ROV** is a modular ROV for underwater inspection and intervention which comes in three basic configurations. It is made of composite materials to reduce weight and for added performance. It has advanced thrust and power control for operations in difficult environments. Its dimensions are 120 x 70 x 90 cm and its weight is 90 kg. It has 5 Seaeye SI MCT01 thrusters, a maximum operating depth of 200m and power consumption of 3Kw. It has the same inspection and navigation packages installed on the IES ROV plus a 2-degree of freedom robotic arm for interventions. It can also mount additional payload on a specialized designed instrumentation tray.

The **SWORDFISH ASV** is a 4.5m long Autonomous Surface Vehicle (ASV) based on an ocean-going catamaran (200kg) equipped with two Seaeye SI-MCT01 thrusters. SWORDFISH is a powerful communications node with WiFi and broadband radios, Global System for Mobile communications (GSM) capability and acoustic modems for underwater communications. The standard payload includes a wireless video camera. It is also used as a gateway buoy for wireless and underwater communications. Energy is provided by batteries which can power SWORDFISH for up to 6 hours of operation. It has a GPS unit and a miniature Inertial Motion Unit (IMU) for navigation.

The **ISURUS AUV** is a modified version of a REMUS (Remote Environment Measuring UnitS) class AUV, built by the Woods Hole Oceanographic Institution (MA, USA), for low cost and lightweight operations in coastal waters. ISURUS has a torpedo shaped hull about 1.6 meters long, with a diameter of 20 cm and weighting about 35 kg in air. The maximum forward speed is 4 knots, being the best energy efficiency achieved at about 2 knots. At this speed, it is capable of operating for up to 8 hours. The maximum operating depth is 200m. It uses a PNI TCM2 digital compass and Long BaseLine (LBL) acoustic beacons (20-30 KHz) for navigation. In the standard configuration, it is equipped with an Ocean Sensors 200 CTD sensor, a Wet Labs optical backscatter sensor, a Marine Sonics side scan sonar and an Imagenex altimeter. The communications suite includes a Benthos acoustic modem and WiFi.

The **N AUV** is an advanced version of the ISURUS vehicle. In addition to ISURUS it mounts an Acoustic Doppler Current Profiler and a Micromodem from WHOI.

Our most recent AUV, the **LAUV** is a low-cost submarine for oceanographic and environmental surveys. It is a torpedo shaped vehicle made of composite materials (110x16 cm) with one propeller and 4 control fins. The LAUV has an advanced miniaturized computer system running modular controllers on a real-time Linux kernel. It is configurable for multiple operation profiles and sensor configurations. In the standard configuration, it comes with a low-cost inertial motion unit, a depth sensor, a LBL system for navigation, GPS, GSM and WiFi. The maximum operating time is 8 hours. We have several units of the LAUV in different configurations.

In addition to autonomous vehicles, we have been developing drifters to monitor ocean currents. In their simplest version, our drifters consist of a simple computer system and a GPS/GSM board installed on a waterproof ocean-resistant container. The position of the drifter is monitored in real-time with the help of GSM/GPS communications.

The operation of these vehicles is supported by the LSTS tool chain which implements the LSTS planning and control framework.

Neptus is a distributed command, control, communications and intelligence framework for operations with networked vehicles, systems, and human operators. Neptus supports all the phases of a mission life cycle: world representation; planning; simulation; execution and post-mission anal-ysis. Neptus supports concurrent operations: vehicles, operators, and operator consoles come and go; operators are able to plan and supervise missions concurrently.

IMC is a communications protocol that defines a common control message set understood by all types of LSTS nodes (vehicles, consoles or sensors) in networked environments. This provides for standard coupling of heterogeneous components in terms of data interchange.

DUNE is the system for vehicle on-board soft-ware. It is used to write generic embedded soft-ware at the heart of the vehicle, e.g. code for control, navigation, or to access sensors and actuators. It provides an operating-system and architecture independent C++ programming environment for writing efficient real-time reactive tasks in modular fashion.

DFO (Data Flow Objects) is a coordination language for the specification of supervision control software, deployed on top of DUNE. It is used for supervision of mission execution, vehicle state, and embedding manoeuvre controllers. In conjunction with the toolchain, it is being extended to accommodate for more expressive notions of autonomous vehicle execution that provide support for: cooperative vehicle missions, dynamic exchange of control links between network entities, or on-the-fly mission re-programming.

Seaware is an interface for publish-subscribe messaging, deployed on top of the Real-Time Innovations DDS tool. It supports dynamic coupling of network nodes and configurable network QOS.

Test Scenarios

In order to test and evaluate the capability of NOPTILUS to successfully address the objectives (O1)-(O8) under realistic conditions we have defined **three basic test scenarios** where the NOPTILUS system and its various components will be tested in an incremental fashion and by increasing mission's (scenario's) complexity. In all three basic scenarios, the NOPTILUS multi-AUV system will be tested under different simulated sea-accidents involving the spill of a chemical. Please notice that for environmental reasons, the chemicals that will be used during the scenarios are "environmental friendly" and cause no damage or pollution (more precisely, ink, rhodamine and/or fish oil will be used). Please also note that for each of the basic scenarios we will develop tests and demonstrations in an incremental way and conforming to a spiral development model. The three basic NOPTILUS scenarios are as follows:

1. Harbor Scenario (Basic Scenario 1). Under this scenario, sunken drums leaking chemicals will be placed on the seafloor within the harbor (at a maximum depth of 20 meters) and the NOPTILUS system will be called to detect and locate the drums and track the chemical spill. The basic assumption in this scenario is that an accurate map of the seafloor is known and is available to the NOPTILUS system. During base scenario 1, the following attributes of the NOPTILUS system will be tested and demonstrated:

- Localization, i.e. the ability of the NOPTILUS system to keep AUVs accurately localized (by having one of them being re-surfaced, by exploiting their motion to keep localization, etc).
- Relative pose estimation between the AUVs (necessary for the AUVs that have lost GPS fix)
- Fused sonar/vision surface extraction
- Coordinated motion control (the swarm will be asked to perform certain pre-defined coordinated trajectories subject to currents)
- Sensory-motor control (the swarm will be asked to «go towards 1 or 2 different objects subject to currents), when no GPS info is available.
- Multiple process tracking (the AUV swarm will be called to track the spills from 2 or more different drums).

To be able to compare the NOPTILUS system with the current state of the art (humanly-operated ROVs or AUVs), humanly-operated ROVs will be called to accomplish the same tasks as the NOPTILUS system. The time-to-detect and accuracy of tracking between the NOPTILUS system and the humanly-operated one will be compared (it has to be emphasized that in the case of humanly-operated ROVs no cooperation between the operators is taking place as each of the operators is assigned a different area and each operator "operates" in their area without taking into account what the rest operators do).

2. Coastal Shipwreck (Basic Scenario 2). Under this scenario, sunken drums leaking chemicals will be placed on a real shipwreck outside the harbor (at a maximum depth of 60 meters) and the NOPTILUS system will be called to (a) detect, locate and map the shipwreck and (b) detect, locate and track the chemical spill. As in basic scenario 1, the basic assumption in this scenario is that an accurate map of the seafloor is known and is available to the NOPTILUS system (but the exact location of the shipwreck is not known). During base scenario 2, the following attributes of the NOPTILUS system will be tested and demonstrated:

- switched motion/sensory motor control

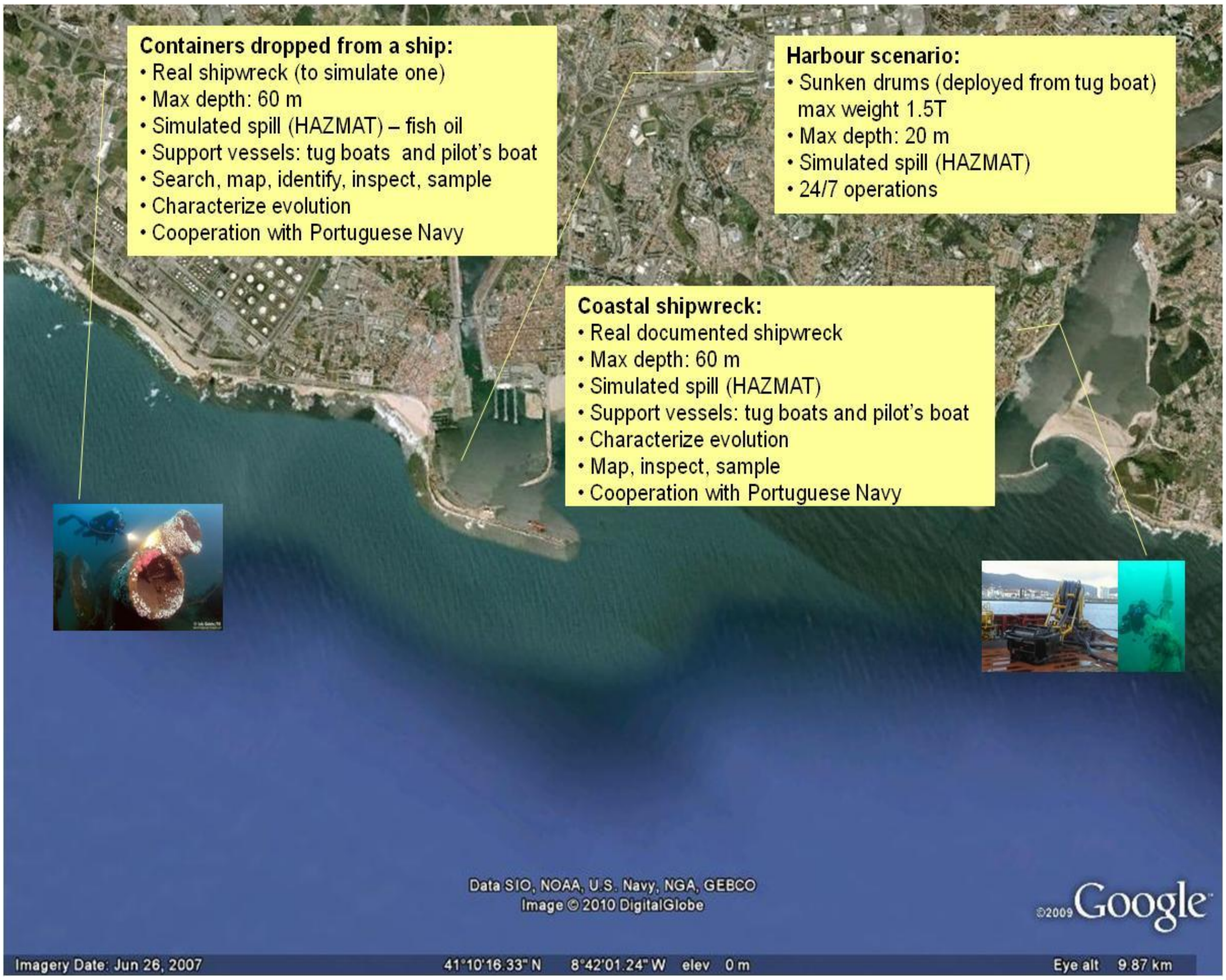
- map creation and spill tracking, (first under pre-defined trajectories), and then
- by having the NOPTILUS system automatically generating the AUV trajectories so that map/spill tracking accuracy are maximized.

As in base case scenario 1 and to be able to compare the NOPTILUS system with the current state of the art (humanly-operated ROVs or AUVs), human-operated ROVs will be called to accomplish the same tasks as the NOPTILUS system. The time-to-detect and accuracy of tracking between the NOPTILUS system and the human-operated one will be compared (as in the case of basic scenario 1, no cooperation between the operators is taking place as each of the operators is assigned a different area and each operator "operates" in their area without taking into account what the rest operators do).

3. Containers Dropped from a Ship (Basic Scenario 3). This scenario intends to simulate the NOPTILUS system performance when deployed to prevent an ecological disaster due to the sinking of a ship carrying liquid chemicals (like the example described in section B.1.1.1). More precisely, and in order to simulate the sinking ship, containers will be dropped from a ship (outside the harbor at a location with maximum depth 60 meters and experiencing mild currents and waves); By the time the containers reach the seafloor they will start leaking chemicals. The containers will "land" on or close to a real shipwreck (in an attempt to simulate the process of a real ship sinking). Contrary to basic scenarios 1 and 2, the seafloor map will be assumed totally <u>unknown</u> to the NOPTILUS system. The NOPTILUS system will be called to concurrently (a) built a map of the seafloor, (b) detect, locate and track the container/shipwreck (while its sinking and when stabilized at the seafloor) (c) provide a clear map of the shipwreck and (d) detect, locate and track the spill after the containers have touched the seafloor and they start leaking.

The overall NOPTILUS system will be demonstrated and evaluated during this scenario. Of particular importance during this scenario will be the demonstration of the ability of the NOPTILUS Situation Understanding module to be able to recognize and understand dynamic underwater phenomena. For this reason, artificially imposed incidents (e.g. one of the AUVs getting caught on a fishing net or losing contact with the central control) will also take place during this scenario and the NOPTILUS Situation Understanding module will be called to recognize these incidents.

It has to be emphasized due to the complexity of the particular mission of base scenario 3, such a mission cannot be accomplished by human-operated ROVs or AUVs. As a result, a successful accomplishment of basic scenario 3 by the NOPTILUS system will be one of the most significant outcomes of the project.



The NOPTILUS Basic Scenarios

Porto University and the Portuguese Navy signed a Memo of Understanding (MOU) in 2007 to promote the cooperative development of unmanned vehicles. Under this MOU Porto University and the Portuguese Navy carried out several research and development projects and performance joint deployments. Under this cooperation, researchers from Porto University spent over 6 weeks at sea operating autonomous vehicles. This cooperation is due to continue at least for the duration of the project. In the context of this cooperation the Portuguese Navy provides support to operational deployments either from Bacamarte, a 60m long ship developed to support amphibious operations, or from Zodiac boats. NOPTILUS operational deployments can be aligned with some of these deployments. This means that Noptilus will benefit from unique access to sea and to operations,

In addition to the cooperation with the Portuguese Navy, the Porto Harbour also provides support to operational deployments with Zodiac boats, or with 15m long vessels capable of operating at sea.

Apart from the above described basic scenarios, some preliminary underwater tests will be conducted on Month 18 of the project for testing the communications, underwater vision and sonar-based mapping modules of NOPTILUS. As the testing of these modules does not require that the overall AUV team is deployed during the tests and, moreover, no autonomy is required, these preliminary tests will be conducted by one (or two in the case of testing the communication modules) ROVs.

The Table below presents briefly the timing and the objectives to be tested during the preliminary tests and the 3 basic Scenarios.

What	Objective	When	WP	Scenario
Communication Sonar-based mapping Vision	O3 O5 O6	M18, M18-M30	3.1 3.2 3.4	Underwater Tests inside/outside port/Simulation Evaluation
Localization Relative pose estimation Fused sonar/vision surface extraction Coordinated motion control Sensory-motor control Multiple process tracking	O4 O7 O6 O8	M30	3.3 3.5 4.1 4.2 5.1 5.2	Harbor Scenario (seafloor map known)
Switching motion/sensory-motor control Map construction and process tracking PAN for optimizing estimation accuracy	O1 O7 O8	M42	4.1-2 5.3 7	Coastal shipwreck (seafloor map unknown)
The overall NOPTILUS system (w/ and w/out the aid of surface vessels)	All	M43-M48	All	Containers dropped from a ship (seafloor map & shipwreck unknown)

Apart from the 3 basic scenarios, and in close cooperation with APDL, we will also define and test other possible missions that can take place during project's lifetime. More precisely, we will consider six representative types of operations to address the NOPTILUS objectives/challenges: i) detailed benthic mapping with adjustable resolution (harbor in general, navigation channel and access routes) ii) inspection of underwater infra-structures; iii) inspection of dredged and dump sites; iv) rapid environmental assessment and environmental monitoring with unprecedented spatial and temporal resolution; v) inspection of ship hulls and other mobile structures; and vi) support to disaster management. Common to these operations are the requirements for: a) precise geo-location (for re-visit, re-evaluation and multi-sensor fusion); and B) on-demand or persistent operations. Today most of these operations are not automated and rely heavily on divers. This provides a base-line for the evaluation of our developments.

It should be stretched out that the 3 NOPTILUS basic test scenarios as well as the above-described six representative types of operations do not involve or imply any potential military aspect or use of NOPTILUS services for military purposes and refer to pure civilian operations inside or outside the port infrastructure.

B1.1.5 Measurable Objectives

A set of clear and straightforward to calculate and assess targeted measurable objectives and quantifiable operational goals should be defined in order to evaluate the efficiency and applicability of the NOPTILUS system. These objectives and goals should be capable of quantifying the ability of the NOPTILUS system to address the S&T objectives listed in Section XX1.1.2. The evaluation of NOPTILUS's capability to address these S&T objectives will be based on the real-life data collected at the NOPTILUS Test Case during the integration weeks and – mainly – during the demonstration period. Three different sets of measurable objectives have been identified and are described in the Table below.

NOPTILUS Measurable Objectives	
NOPTILUS S&T Objectives	**Description & Targeted Goals**
Efficient Performance	For NOPTILUS Basic Test Scenarios 1 and 2, the performance of the NOPTILUS system and that of a humanly-operated system of AUVs/ROVs will be compared. The NOPTILUS goal will be to accomplish the particular mission in • at most 50% of the time required using divers or human-operated AUVs/ROVs. • at least, the same accuracy (as far as it concerns maps, recognition and situation understanding) as the one obtained using divers or human-operated AUVs/ROVs. • at most 10% of the cost required using divers or human-operated AUVs/ROVs.
Ability to Accomplish Missions that Humanly-Operated Systems Cannot	A successful accomplishment of basic scenario 3.
Nearly-Optimal Performance	Nearly-optimal or "arbitrarily-close-to-optimality" is one of the most ambitious promises of NOPTILUS; Unfortunately, such a promise is very difficult to be verified using real-life data as it will not be practically possible to implement in real-life the optimal AUV-system decisions in the Test Case operations. To overcome this difficulty, the operations in the 3 basic scenarios will be modeled using realistic, high-fidelity underwater simulation and the optimal AUV actions will be computed in simulation. The NOPTILUS performance will be then compared to the optimal one and the NOPTILUS operation goal will be to provide • a performance that is, at least, 5-10% close to the one of the optimal (with respect to both time and mapping and situation understanding accuracy) solution. The – nearly – optimality of the NOPTILUS multi-AUV system will be assessed with regards to the following performance index:

<table>
<tr><td></td><td>

$$J = E\left[\int_0^T \left(\sum_{i=1}^{N} q_i \left(x_i(t) - \hat{x}_i(t)\right)^2 + \sum_{i=1}^{M} p_i \left(e_i(t) - \hat{e}_i(t)\right)^2\right) dt\right]$$

where the mathematical symbols in the above performance index are defined as follows:
T time-duration of the mission;
N total number of features to be estimated. The features may include landmarks, position and orientation of AUVs (for localization), location of moving targets and processes, grid locations (for mapping purposes);
$x_i(t)$ vector denoting the location of the i-th actual feature;
$\hat{x}_i(t)$ vector denoting the estimation of the location of the i-th actual feature as generated by the NOPTILUS system;
q_i positive parameter giving a weight to particular features (for instance, for features that is required more accurate estimation than the rest, the corresponding weight should be comparatively large);
M total number of possible underwater events;
p_i positive parameter giving a weight to particular event;
$e_i(t)$ a binary variable that takes the value 1 if the i-th event is active and 0, otherwise;
$\hat{e}_i(t)$ the estimated value for $e_i(t)$ as generated by the NOPTILUS system;
It has to be emphasized that in the case of the absence of the term $\sum_{i=1}^{M} p_i \left(e_i(t) - \hat{e}_i(t)\right)^2$ the above-defined performance index reduces to the classical performance index of multi-robot teams employed for pure estimation tasks (i.e. map construction, dynamic process tracking, localization or combination of any of the three). The addition of the term $\sum_{i=1}^{M} p_i \left(e_i(t) - \hat{e}_i(t)\right)^2$ is made in order to assess the NOPTILUS capability to – in parallel to performing estimation tasks – recognize and understand dynamic underwater events.
</td></tr>
<tr><td>Efficiency, Robustness and Accuracy of NOPTILUS particular modules</td><td>Finally, a set of clear operational goals with respect to all low- and medium-level NOPTILUS modules will specified in D2.1 and D8.1. More precisely, the communication, processing and accuracy requirements of all low- and medium-level NOPTILUS modules will be agreed between all the partners involved in the design, interfacing and integration of these modules and specific targets (e.g. with respect to the accuracy of mapping and localization, etc) with respect to these goals will be defined.</td></tr>
</table>

B1.2 Progress beyond the State-of-the-Art

In the following the objectives listed in Tables 1 and 2 of the proposal are shortly addressed and the state-of-the-art discussed, according to the Table shown below:

State-of-the-Art and NOPTILUS approach with respect to Objectives (O1)-(O8)		
Objective (O1)	Situation Understanding	See section B1.2.8
Objective (O2)	Planning, Assignment & Navigation	See section B1.2.9
Objective (O3)	Underwater Communications	See section B1.2.1
Objective (O4)	Underwater Localization	See section B1.2.2
Objective (O5)	Underwater Sensing	See section B1.2.3
Objective (O6)	Underwater Vision and Fusion	See section B1.2.4
Objective (O7)	Estimation for Map Construction & Process Tracking	See sections B1.2.5
Objective (O8)	Motion and Sensory-Motor Control	See sections B1.2.6 and B1.2.7

It has to be emphasized that, apart from objectives (O1) and (O2), successfully addressing each and single of the low- and medium-level objectives (O3)-(O8) is necessary and crucial for the development of the fully-autonomous NOPTILUS system. For instance and with regards to objectives (O3) and (O5), if existing communication and sensing designs were employed within NOPTILUS, their limited accuracy would lead to poor estimation results (e.g. inaccurate maps) which, in turn, would have the result of "confusing" the Situation Understanding and PAN modules, leading the overall NOPTILUS system to non-optimal – or even totally erroneous – decisions. The "seeing through murky waters" vision and combined sonar/vision systems – objective (O6) – are necessary for rendering the NOPTILUS system capable of extending the operation range of multi-AUV systems, e.g. by taking over inspection tasks where sonar measurements are not able to provide accurate and detailed information (e.g. for detecting the locations in a shipwreck where chemicals are leaking). In case localization is lost or has become very poor, it is not possible to apply motion control anymore and in such cases there is the need for switching to sensory-motor AUV control – objective (O8) – which will make sure that the NOPTILUS system will keep operating efficiently and optimally. Localization, however, cannot be absent or poor over long periods of time in situation awareness operations: the NOPTILUS system should be able to regularly "recover" accurate localization information in order to globally localize the maps it has constructed and the static or dynamic features it has detected; To do so, new designs and concepts in underwater localization – objective (O4) – are required. Finally, and when localization information is available (or has been recovered), there is a crucial need for the AUVs to strictly obey the path planning commands of the NOPTILUS PAN; strong currents and turbulences may cause the AUVs to severely deviate from the assigned paths and the existing motion control designs are not always able to "bring" the AUVs back to their assigned paths in such cases. New, efficient motion control designs are needed – objective (O8) – that are capable of learning and predicting the currents/turbulence effects and characteristics and compensate them in an optimal fashion.

B1.2.1 UNDERWATER COMMUNICATIONS

Worldwide, increasing effort is put into research on underwater communication systems with many of the results originating from the field of wireless communications. However, the acoustic underwater communications channel is quite different from the electromagnetic wireless communications channel and as such radically different physical layer and networking techniques must be introduced so as to support the autonomous operation of multi-AUV systems.

The acoustic channel. The underwater acoustic channel is quite possibly nature's most unforgiving wireless communication medium [C1]. Absorption at high frequencies, and ship noise at low frequencies, limit the usable bandwidth to a few (tens) of kilohertz, depending on the range. Horizontal underwater channels are prone to multipath propagation due to refraction, reflection and scattering – this is especially true in clean-up operations where the physical properties of the communication medium can have significant spatial variations. The sound speed of 1.5 km/s is low compared to the speed of light and leads to channel-delay spreads of tens or hundreds of milliseconds. In certain environments, reverberation can be heard ringing for many seconds and ultimately limits the performance of communication systems. The low speed of sound is also responsible for significant Doppler effects, which can be subdivided in (time-varying) frequency shifts and instantaneous frequency spreading due to various mechanisms [C2]. Both phenomena contribute to the Doppler variance of the received communication signals, and require different measures to be taken at the receiver. A channel displaying both time-delay and frequency dispersion is known as a doubly spread channel. If the product of delay spread and Doppler spread exceeds unity, then the channel is known as being overspread, and there is little hope for reliable communication.

Apart from covert applications, the performance of underwater communication systems is normally not limited by noise but by multipath and Doppler. This implies that it is not possible to increase the feasible data rate to an arbitrary value by increasing the SNR. Acoustic modems used in underwater networks often operate at a data rate of no more than a few hundred bits per second. High(er) data rates are feasible, depending on the environment and conditions, but for robust operation an array of receivers is required.

Physical layer considerations. Until the mid-nineties, research in underwater communications had mainly focused on the physical layer, i.e., the communication transmitters and receivers for the transmission of raw bits. A breakthrough was achieved in the mid-nineties by Stojanovic et al., who showed that phase-coherent communication, e.g., phase-shift keying (PSK), is feasible by integrating a phase-locked loop into a decision-feedback equalizer [C3, C4]. Such a receiver can be applied to a single hydrophone, although robust operation at high data rates, say several Kbps, generally requires the presence of a (vertically-placed for best performance) hydrophone array for reception. Indeed, multichannel adaptive equalizers have proven to be versatile and powerful tools [C3, C5, C6]. If the use of a receiver array is impractical, as in multi-node networks, then frequency-shift keying (FSK) is often used as a fairly robust modulation for single-receiver systems [C7, C8, C9]. However, the corresponding data rates are of the order of a few hundred bit/s.

Recently, the use of multicarrier modulations has been investigated for underwater communications [C10, C11, C12, C13, C14], mainly due to its popularity in wireless communication standards. When the channel is time-invariant over a single symbol, equalizing multicarrier modulations is very simple. However, due to the strong Doppler present in underwater communication channels, the channel introduces inter carrier interference (ICI), and classical equalization schemes do not apply anymore. Special schemes have been developed to deal with ICI, but these techniques often assume that all paths of the underwater acoustic channel have the same Doppler shift. However, recently emerging experimental evidence, as well as theoretical modeling, suggest that such models are in fact not appropriate for underwater acoustic channels. Instead, each path in a multipath underwater channel has a different Doppler shift, which negatively impacts the receiver's performance. Unfortunately, there exists no body of work suggesting how this property should be treated in multicarrier communications. Finally, extensions of multicarrier systems to a (vertical) array of multiple hydrophones have yet to be studied in depth, although these multiple channels could be exploited to reduce ICI.

Networking considerations. There is no single acoustic communication network that will satisfy all possible needs, and thus different applications may require different approaches in many layers of the network. Underwater network designers find themselves confronted with many challenges. A major difficulty is the latency caused by the relatively low sound speed. Typical travel times between nodes are many orders of magnitude longer than in radio frequency networks. Energy efficiency is also an important design criterion [C15]. The energy consumption of acoustic modems is generally in the range of 5-50 watt while transmitting. The recovery of bottom nodes for battery recharge is a costly operation and modems are also a major burden for the limited battery capacity of AUVs. Another optimization criterion is network throughput. It is well-known that the data rates feasible with acoustic communications are orders of magnitude lower compared to radio frequency rates, while the routing overhead of the network layer further reduces the net data rate. Regardless of the functional demands and design priorities, medium access control (MAC) is an important ingredient of underwater networking. Without MAC, there is a high risk of collisions in a cacophony of unsolicited modem transmissions. In order to avoid this situation, measures are necessary for controlling access to the medium of different users. Generally, a distinction can be made between contention free (or deterministic) and non-contention free (or random access) MAC protocols [C16].

Contention-free protocols can be further subdivided into time-division multiple access (TDMA), which assigns different time slots to users, frequency-division multiple access (FDMA), in which users transmit in different frequency bands, and code-division multiple access (CDMA), where orthogonal (pseudo-random) codes are used between users. In the last case, signals transmitted by different users can – in principle – be received at the same time and in the same frequency band. Each of these basic methods has weaknesses and strong points. For example, a weakness of TDMA is that travel times change continuously with moving nodes. FDMA is sensitive to the frequency-selective fading inherent to multipath environments when narrow subbands are used for a single modem type, and puts high demands on hardware if modems with different passbands are used. CDMA is only feasible when the received sound pressure levels of different users are approximately the same, which is difficult to guarantee. Instead, we propose to further investigate and expand Cognitive MAC (C-MAC), where every link comprising a transmitter and a receiver senses the amount of interference present and reacts to that by adapting its transmission in order to optimize the link throughput. Such a MAC fits very well the multicarrier physical layer discussed above, where the transmission can be optimized using power/bit loading of the different carriers. Further enhancements of the overall network throughput can be obtained by allowing neighboring nodes to collaborate with each other.

Besides the above contention free protocols, a plethora of non-contention free protocols have been proposed for radio frequency and underwater networks, see e.g. [C16, C17]. The ALOHA protocol is based on random access to the medium. Whenever a user has data to send, it transmits a data packet. An acknowledgement (ACK) is sent back to the receiver if the packet is received without errors. If packets get lost, the receiver does not issue an ACK and the sender retransmits the packet after some (randomly selected) time. Carrier sense medium access (CSMA) protocols try to avoid collisions by listening for a signal prior to transmission. Users who have information to send, but detect transmissions of other modems in progress, will wait until the channel is clear. Because of the long propagation delays, and because not all nodes can hear all other nodes, this does not prevent collisions at the receivers. The Multiple Access with Collision Avoidance (MACA) protocol attempts to avoid collisions at the receivers. This protocol uses request-to-send (RTS) and clear-to-send (CTS) handshaking commands prior to transmission of the actual data. Recent proposals include the energy efficient T-Lohi MAC [C18] and the receiver-initiated packet train (RIPT) protocol for multihop networks [C19].

Advances over the state-of-the-art

- As discussed above, multicarrier modulation is an excellent candidate for underwater acoustic communications. Such systems have the ability to reach high throughputs in an underwater environment, but it is necessary to adapt the system to account for the different Doppler shifts of the different paths of the channel. To address this issue, we will correlate the received signal with different Doppler-shifted versions of the transmitted waveform in order to capture all the energy that is present in the received signal. The resulting correlator outputs will then be efficiently combined to obtain the transmitted information symbols. Note, that this approach requires estimating the amplitudes, time delays, and Doppler shifts of the different paths of the propagation environment, which will be achieved by designing novel pilot sequences.
- The throughput and/or reliability of a multicarrier communication system can be improved by employing a (vertical) hydrophone array. The availability of multiple output channels can also be exploited to tackle the Doppler effects introduced by the underwater channel. Specifically, we will use the diversity of the multiple channels to remove the inter carrier interference in a multicarrier system. Basically, every extra output channel creates a new equation in the same number of unknowns (the transmitted information symbols), and thus there is more redundancy in the system which leads to improved performance and increased reliability
- Recent results shows that, when different paths are affected by different Doppler shifts, there may exist better transformation-based modulation schemes than multicarrier modulation. For instance, the Mellin transform is known to be a scale-invariant transformation that can transform a linear combination of a set of weighted and scaled versions of a pulse into the Mellin transform of that pulse multiplied with a factor that depends on the weights and scales. However, when the different pulses are also delayed in time, the Mellin transform does not have a particularly interesting form. To address this limitation, we plan to investigate methods for adapting this transformation in order to explicitly consider time delays.
- We will also study a C-MAC layer where the interference will be sensed and the transmission of a multicarrier signal will be adapted accordingly by means of power and bit loading. This is very reminiscent of current work carried out in the field of cognitive radio, where every cognitive radio (consisting of a transmitter and a receiver) opportunistically gains wireless access by claiming resources (e.g., carriers) that are used at that point in space and time. We plan to transfer this cognitive radio principle to the underwater arena, where it will need to be adapted and extended so as to deal with the additional challenges of Doppler spread and latency.
- To further improve the overall throughput of the network, collaborative communication schemes will be developed in combination with the above C-MAC. It is well known that the optimal throughput of the C-MAC layer discussed above (which constitutes a form of Nash equilibrium) can be much lower than what could be achieved by a central control unit that gathers all the information. Hence, we plan to investigate methods for improving the C-MAC throughput by adding a collaborative element to the system. Possible tools to reach a better throughput are Nash bargaining or interference pricing.

B1.2.2 UNDERWATER GLOBAL LOCALIZATION

The current practice in underwater localization is based on sonar, motion sensing, and the occasional GPS fixes when the AUV surfaces. Each AUV uses its own sonar and gyroscope/accelerometer/propeller units to track its position when underwater, possibly aided by one or more surface “anchors” (i.e., emitting sonar beacons). This approach maintains full autonomy of each AUV, yet leaves much to be desired in terms of localization accuracy, early warning capability, fault tolerance and other attributes that are crucial in mission-critical operations.

Most of our know-how in localization is based on experience gained from terrestrial localization using radio waves – from GPS to cellular radio, and, more recently, related problems in wireless sensor networks. One of the lessons learned from the latter is the importance of cooperation in ensuring accurate localization in difficult scenarios – and the underwater environment is one of the harshest in terms of multipath, Doppler, and wavefront aberration. We will therefore consider cooperative swarm localization approaches that pool together information from the different AUVs. Suppose that each AUV can measure its distance from a few other AUVs, and possibly also landmarks and beacon nodes. Individual measurements will usually be incomplete, and may not allow obtaining a unique (let alone accurate) position fix. The question is how we can combine these individual measurements to improve localization performance for all, in a way that respects the constraints (e.g., on communication rates and latency) of the underwater environment.

Given pair-wise distances between certain entities, the problem of finding points in 2-D or 3-D space that generate those distances is known as Multi-Dimensional Scaling (MDS). MDS has its roots in Psychology [L1, L2, L3], but it has found abundant applications in many areas, including, for example, multimedia search and sensor network localization [L5, L6, L7]. Consider *N* nodes (e.g., cities, mobile phones, or AUVs), with given pair-wise distances. The problem is to find *N* points on the plane (or in 3-D space) whose Euclidean distances are (approximately) equal to the given pair-wise distances between the nodes. One concern is that the distance between points is invariant with respect to rotation, reflection, and shift – hence the reconstructed map will not have the customary orientation. One needs at least three (in the 2-D case) *anchor* nodes whose absolute coordinates are known (e.g., via GPS) to resolve these ambiguities.

Research to date on MDS has generated a diverse array of algorithmic solutions, starting with centralized ones based on Singular Value Decomposition of the doubly-centered distance matrix [L1, L2], to distributed ones tailored for wireless sensor network applications, and also capable of handling missing data [L6]. Work to date also includes means for clever initialization (see [L7, L4] and references therein), iterative refinement, and incorporation of prior knowledge. MDS remains a difficult non-convex problem that continues to generate significant interest in terms of basic research and new applications.

In our specific context, there are numerous challenges to successful application of MDS ideas for cooperative AUV localization:

Multipath and path loss (error) models: Distance from a beacon / landmark or other AUV is derived from time delay and/or received signal strength measurements. Accurate localization (e.g., by means of Maximum Likelihood refinement) requires appropriate statistical models of multipath and path loss for the underwater acoustic channel. There is very little modeling work to date on related issues, and this is primarily in the context of de-reverberation / equalization.

Fusion of distance and motion information: Unlike mobile phones or sensors, AUVs are equipped with rather sophisticated motion sensing instruments that provide valuable information.

We will investigate ways of fusing distance estimates and motion information to improve localization accuracy and track the location of each AUV in a distributed yet collaborative manner.

Anchoring: A key issue is how to anchor the solution and ensure limited uncertainty when the AUVs are submerged most of the time, and no beacons can be deployed on the surface. One possibility is to have one or more AUVs re-surface when needed to obtain a GPS fix. A single AUV can take multiple GPS readings while it is moving and others are measuring distances to it – thus yielding multiple anchors. The geometry of these measurements is important, as, e.g., three GPS readings on a line cannot disambiguate the three degrees of freedom. We will investigate optimizing the schedule of GPS readings to minimize localization error.

Dealing with severely limited communication rates: Work to date on MDS for cooperative localization in wireless sensor networks assumes that i) sensors are static or move very slowly relative to distance acquisition; and ii) there is sufficient bandwidth so that timely and frequent communication between adjacent nodes is possible. Neither of the above holds in our present context. Underwater acoustic communication rates are limited to a few kilobits per second (or even lower) in realistic scenarios, and AUVs may glide at non-negligible speeds relative to wave propagation. These constraints demand serious re-thinking of distributed implementations of MDS, including judicious quantization of the distance estimates.

Exploiting swarm motion to disambiguate: A very interesting observation that goes back to [L3] is that if one computes distances once, then scales the axes (e.g., contracts all x-coordinates by a certain factor, and all y-coordinates by *another* factor) and computes distances again, there is a unique solution to the localization problem. This is a remarkable fact that has spawned considerable interest in a field known as three-way analysis. In our present context, it is intriguing to consider exploiting "swarm" motion to generate multiple sets of distances corresponding to different scaling of the x-y-z axes. Even if exact scaling of the axes cannot be accomplished this way, working with a set of distances acquired under motion can lead to an over-determined problem not suffering from rotational ambiguity. This is a very promising research direction to be explored as part of the work to be undertaken in NOPTILUS.

B1.2.3 UNDERWATER ARRAY SENSING

Existing practice is that each AUV maps landmarks and obstacles using its own sonar, independently of other AUVs. Maps are sometimes "swapped" and logically merged later, but there is no coherent combining during the initial mapping stage (at the signal level). In traditional radar, multiple transmit antennas are combined in a phase-coherent fashion to beamform – direct the illumination or focus reception along a particular direction of interest, but this requires tight synchronization. A relatively recent technological advance in radar technology is multiple-input multiple-output (MIMO) radar, wherein the transmitter employs multiple transmit antennas to emit a set of orthogonal waveforms – a different one from each transmit antenna. It has been established that MIMO radar offers significant diversity / resolution benefits relative to traditional phased-array radar [L8, L9, L10].

MIMO radar ideas are currently breaking into the sonar arena – there are few mature pieces of work in the area, but a few groups have started looking at MIMO sonar; cf. [L11,L12]. What we are interested in, however, is distributed (virtual) MIMO sonar – meaning that sonars from different AUVs are combined to improve resolution in a way akin to the case of multiple sonars mounted on a single AUV. Since MIMO techniques require relatively accurate synchronization, what we advocate here is to `mate' nearby AUVs in pairs. This has a number of benefits: it is easier to synchronize nearby AUVs, the communication channel between them is a lot better – supporting relatively high data transmission rates – and finding a mate should be easy in swarm mode. The following research issues must be addressed to bring the proposed virtual MIMO sonar concept to fruition:

Motion locking and Doppler shift: Relative motion between two AUV mates is an issue, as it implies different Doppler shifts and possibly different multipath channels. This implies that the AUVs in a pair should be motion-locked to within acceptable tolerance. Appropriate mechanisms for achieving this should be devised. Such locking is automatic between neighbors in swarm mode, which suggests that pairing and motion locking can be achieved by mimicking swarm-inducing mechanisms.

Waveform design and synchronization: Due to the severe nature of multipath in the underwater acoustic environment, special care should be exercised in designing appropriate orthogonal codes for the different sonars. A simple option is to use pseudo-random codes, but these require long lengths to ensure quasi-orthogonality. Multicarrier codes are another option that we will explore. Waveform synchronization is important in both transmit- and receive- ends to reap the MIMO gain.

Cognitive sonar: There has been considerable recent interest in *cognitive radar* [L13], whose key premise is that the transmitter should learn and adapt to the environment it senses – i.e., change its illumination pattern to better explore the search space and narrow-down the targets faster. We envision similar developments in sonar. This is completely uncharted territory in the sonar community as of this writing, and we will devote part of our effort to exploratory research in this direction.

B1.2.4 Underwater Active Vision

Traditionally only sonar sensors have been used for detecting targets underwater. This is because sonar can operate over long distances, and in water with poor visibility and lighting. Sonar, however, has two main drawbacks: it does not yield the albedo of the sensed surface and it is not reliable for targets closer than 5m, i.e. for tasks like docking and inspection. In recent years, vision has been investigated intensively for use with underwater robots and unmanned vehicles, in order to overcome the above shortcomings [V1]. One of the main issues is liaising the control (in case of sensory-motor control) of the vehicle with the information extracted from the images. Papers with emphasis on the control part, tend to use very elementary image processing (e.g. [V2] which is concerned with the automatic tracking of underwater pipelines), while papers that elaborate on the imaging part tend to ignore the importance of using this information for the control of the vehicle. Some of the works that concentrate on the imaging part are concerned with the design of landmarks painted on the targets, so that they are easily identifiable from a large number of distances (e.g. [V3, V4]). Using predefined landmarks to identify the target is appropriate for inspecting known targets, but not for identifying new unknown targets or targets belonging to un-cooperating agents (e.g. detecting and identifying underwater mines). The problems of using vision in underwater tasks are caused by many factors, including poor lighting conditions, vehicle vibration and drift due to underwater currents, and the presence of plankton that reduces significantly the optical depth of the water. To overcome the issue of poor lighting conditions and to be able to infer the 3D shape of the imaged surface, structured light has been successfully used for 3D shape reconstruction in industrial inspection applications [V5]. The use of structured light belongs to the category of active sensing, like sonar. In this case, however, a regular grid of light is projected on the sensed surface and imaged by a camera. The regular grid is deformed according to the shape of the surface, and from the deformation the 3D shape of the surface may be inferred. This implies that the camera has to be able to image the projected light pattern reasonably accurately. In murky waters, however, there is a very strong back-scattering component that reduces significantly the quality of the captured images. To overcome this limitation, some researchers have proposed elaborate devices, using for example, an array of cameras with technology borrowed from confocal microscopy [V6]. Such devices, however, tend to be pretty expensive. Other approaches involve the use of polarimetry [V7, V8].

Recently, researchers have realized that there is a lot to be gained by incorporating in the image-processing task the physics of the image creation process. Thus, we had the ground-breaking work by Oakley and his collaborators, who developed a system for “seeing through fog”. Their system worked in real time for aircraft and allowed the pilot to have projected on a screen in front of him what he was supposed to be seeing from his window through the fog between his plane and the ground. This was achieved by modeling carefully the process of light scattering by the fog droplets [V9, V10]. A similar approach has been adopted in [V11] for dealing with the scattering of light in murky water. These authors considered also the use of photometric stereo for recovering not only surface relief, but also surface albedo. However, their experiments were all done using a tank of water with added milk. Photometric stereo [V12, V13] is a technology that uses several images of the target, captured under different lighting directions, and combined to determine the shape and albedo (color) of the surface. In a sense, photometric stereo is an active way of sensing (as it uses its own light), but it does not require any special lighting devices, other than 4 or 5 strong directional lights placed at the corners of the vehicle, and synchronized with the camera. This way, 4 or 5 images of the imaged surface have to be captured in quick succession, with only one of the lights being on when an image is captured.

In the NOPTILUS proposal, and in order to determine the surface albedo and 3D shape of objects of interest, we plan to extend the capabilities of photometric stereo by modeling the scattering of light through the debris that is suspended in the water (e.g. plankton). As a result of this effort, the state of the art will be advanced in several ways:

1) The findings of vision-based 3D surface reconstruction will be fed to the sensory-control system directly, to aid navigation. Thus, an elaborate sensory-motor control system will be combined with powerful image processing technology.

2) The distribution of the shape and size of the suspended particles in murky waters will be estimated in order to model the propagation of the light in underwater environments. Thus, the state of the art of underwater photometric stereo will be advanced as a more realistic modeling of the scattering process will be developed and used.

3) The sensory-motor control system developed will use the albedo information extracted by the photometric stereo only for inspection tasks, while for navigation only the extracted 3D shape information will be used. Thus, the system developed will be able to combine inspection tasks as well as navigation and docking.

4) The shape information extracted with photometric stereo will be combined with sonar information, taking into consideration the uncertainty present in each type of measurements. This is a challenging problem of information fusion, which requires merging two images acquired by two totally different modalities, whose optimal functionality occurs at different ranges. The fusion of these two modalities will allow the vehicle to operate optimally at large, as well as close distances over a wide range of visibility conditions.

It has to be emphasized that the vision system to be developed within NOPTILUS will not be able to “see” in each and every case. For instance, the NOPTILUS vision system will be able to provide only information of the type “the AUV is inside the oil spill” in case of an AUV being inside the oil spill. However, in most cases the NOPTILUS vision system will provide significantly improved sensing capabilities as compared to existing underwater vision systems and will be capable to provide with significantly more accurate information than sonar systems for areas that are less than 5m from the AUV. As a result, the NOPTILUS vision and sonar systems will complement each other in the aim of providing significantly more accurate information than that of systems that rely only on sonar systems or on combinations of sonar systems and conventional vision ones.

B1.2.5 Cooperative Distributed Estimation for Map Creation and Process Tracking

AUVs deployed for situation awareness operations (e.g., determining the location of a shipwreck, estimating the spread of a chemical in the water, etc) must be able to determine their position and attitude (i.e., localize) in 3D, create detailed area maps, and track over space and time processes of interest. One of the key challenges is that AUVs cannot rely on GPS or GPS-aided Inertial Navigation Systems (INS) due to signal unavailability. Moreover, the positioning accuracy of AUVs that communicate via sonar, with buoys equipped with GPS receivers, may be insufficient for certain tasks such as maintaining tight formations, or navigating through narrow passages (e.g., underwater caves, compartments of a sunken ship, etc). Key challenges to cooperative underwater localization and mapping are the communication range and bandwidth limitations, the high computational cost and lack of scalable representations, as well as the low reliability due to the presence of measurement outliers and nonlinearities. Current approaches have focused primarily on single-robot simultaneous localization and mapping (SLAM) that incurs quadratic complexity in the number of mapped features [E31] and fail to efficiently fuse information from multiple sensors under severe communication and processing constraints common to AUVs. Moreover, existing low-complexity approximations (e.g., [E15, E27, E4, E5, E6, E9, E12, E3, E36, E10]) provide no performance guarantees, offer no means for selecting and processing the most informative measurements, and can lead to inconsistent and divergent estimators [E1, E11].

Our research objective is to develop robust and scalable, decentralized nonlinear estimators for cooperative localization, mapping, and process tracking whose processing and communication requirements explicitly consider the availability of resources (i.e., CPU, memory, communication topology and bandwidth), and provide graceful degradation in the presence of failures. In particular, we are interested in combining information from multiple heterogeneous sensing modalities (e.g., static or free floating underwater sensors and AUVs of various capabilities) that can be deployed efficiently and collaborate with each other, as well as with existing infrastructure (e.g., surface vessels, underwater sonars, etc) to provide measurements at different spatial and temporal scales. In this effort and in order to increase the system flexibility in terms of both processing and representation ability, we will develop estimation algorithms that create and use Gaussian Processes-based (GPs) [E28, E2] representations of the benthic environment, i.e., for constructing 3D maps of the ocean floor, as well as for describing the spatio-temporal distribution of chemicals or other processes of interest. The main advantage of GPs is that, in contrast to grid-based representations, GPs scale linearly with the number of observations and their density can be adjusted to meet task requirements. Extending existing GP representations to adapt to time and resolution variations while considering the AUVs communication and processing constraints is within the main focus of our proposed research.

Additionally, and in contrast to existing SLAM algorithms that seek to create dense maps of uniform accuracy, we plan to use a fundamentally different approach to develop Sonar-aided Inertial Navigation Systems (S-INS) where sonar observations (e.g., point features or patches) are treated differently based on their information content and localization utility to create maps of adjustable resolution and accuracy. In particular, most tracked features will be first processed, at only linear cost, to precisely estimate the motion of the vehicle [E21]. Subsequently, only a subset of them will be used for creating a sparse geo-referenced map which will be augmented, as needed, to contain additional mapping information at multiple scales and resolutions [E16]. The main advantages of this mapping process are (i) its computational cost can be adjusted seamlessly from linear to quadratic to match the availability of resources while making optimal use of them [E23, E24], and (ii) it provides the necessary flexibility for concentrating sensing and processing resources to areas along the motion direction that are critical for ensuring precise navigation (e.g., in the vicinity of obstacles). Moreover, and as an extension to cooperative localization of large teams of UAVs, we will also employ decentralized estimators capable of optimally selecting the most informative measurements [E18] and processing severely quantized and compressed observations [E29, E22, E33] at computational cost an order of magnitude lower compared to centralized alternatives [E25, E26].

Furthermore, we propose to expand on recent work on extrinsic calibration [E35, E37, E14, E34, E7] to determine the relative position and attitude of groups of AUVs navigating in 3D using sensor-to-sensor observations, such as relative distance, bearing, and speed. This will endow teams of AUVs with the ability to efficiently and precisely fuse spatially distributed heterogeneous sources of information (e.g., chemical sensors, sonars, cameras, etc), while at the same time considering multiple realization of the estimated process (e.g., due to multiple local maxima [E32, E8]). This in turn, will allow human operators to access and manipulate collected information at multiple levels, in terms of scale, vantage point, and mode, hence resulting in increased situational awareness.

The measurements collected by the various sensors, will be communicated, using appropriate dimensionality reduction and quantization techniques [E29, E22, E33], and processed in a decentralized manner [E30] to estimate spatiotemporal processes of interest while making optimal use of the available memory and computational resources. This will become possible not only through appropriate sensor selection criteria (e.g., as the ones designed for cooperative localization [E18]), but also by introducing appropriate relaxations that lead to any-time algorithms as those introduced for SLAM [E23, E24] and cooperative localization [E25, E26]. Moreover, we will leverage recent work on performance characterization [E19, E20, E13, E17] to derive analytical expressions for the lower bounds on the achieved accuracy as functions of key system and environment parameters, such as the number and precision of the sensors used, the distribution and number of features and targets in the environments, and the topology of the relative (i.e., between the sensors) measurement graph. These analytical results will be used for determining the appropriate team of AUVs that must be deployed, so as to achieve certain mission objectives (e.g., map a sunken ship or determine the spread of an oil leak), and for quantifying the loss of performance once approximations are introduced in the estimation process in order to preserve critical resources.

B1.2.6 Motion Control

The highly nonlinear nature of the vehicle dynamics, the presence of strong currents and turbulences as well as the need – in case of coordinated motion – to precisely coordinate the motion of multiple vehicles renders the problem of motion control of underwater vehicles a very challenging task. Although there has been an intensive effort, especially recently, towards developing efficient motion control methodologies for underwater vehicles, see e.g. [M1]–[M9], the problem of accurate and efficient motion control designs for underwater vehicles still remains an open issue. One should note that if exogenous disturbances, e.g. strong currents and turbulences were perfectly known (i.e. measurable and predictable), the problem of accurate and efficient underwater vehicle motion control would have found a satisfactory solution even when coordination between multiple vehicles is required. Unfortunately, the existing – successful in the known-disturbance cases – methods may perform very poorly, or even fail when strong currents or turbulences affect the vehicle. Attempts to *“robustify”* the aforementioned methods lead to very *conservative* control designs, see e.g. [M4], [M5], which result in, e.g., the vehicle moving extremely slowly in order to deal with potential severe disturbances. On the other hand, efforts to enhance these methods with *adaptive or learning* tools, see e.g. [M6]–[M8] (which on-line "learn" the disturbances' characteristics and guide the control design to efficiently compensate for them), have *very poor transient performance*: an intrinsic drawback of the vast majority of adaptive or learning control designs is that the overall system may exhibit an extremely "bad" behavior, during the time-period the adaptive/learning mechanism "learns" the characteristics of the – unknown – disturbances [M10] something that is not acceptable in most underwater vehicle operations.

Within NOPTILUS we plan to employ a recently introduced learning control design [M9]–[M11] that overcomes the limitations of existing adaptive and learning control methods. This new design, by incorporating **concurrent exploitation–exploration mechanisms** (similar to that of many intelligent beings), achieves to rapidly learn the exogenous disturbance characteristics without introducing poor transients. As a result, when such a concurrent exploitation–exploration scheme is combined with an efficient (for the known-disturbance case) control design, it can achieve an overall motion control performance that is about the same as the one that would have been achieved if the exogenous disturbance characteristics were completely known.

In our research work, we plan to combine the recently developed – within the FP7 project Co3AUVs – non-adaptive and non-learning motion control strategies of [M12], [M13] with the concurrent exploitation–exploration scheme of [M9]–[M11]. Note that the motion control strategies of [M12], [M13] have many advantages over competing (e.g. their robustness to currents are significantly higher) and they are appropriate for coordinated motion control, as that required by NOPTILUS applications. Their combination with the concurrent exploitation–exploration scheme of [M9]–[M11]. is expected to lead to a highly robust and efficient multi-AUV motion control scheme, especially in cases of strong currents and turbulences.

Extensive simulation studies, as well as real-world experiments with the NOPTILUS AUVs at the NOPTILUS test site (Integration Week 2) will be performed in order to investigate different ways to combine the aforementioned control designs and improve their efficiency, adaptability, robustness, and time response characteristics.

B1.2.7 Sensory-motor Control

Autonomous navigation of a mobile robot, equipped with onboard sensor(s) to perceive external world (sonars, laser telemeters, cameras), has been widely studied in robotics. There exist two main approached to autonomous navigation: (a) reactive navigation where the robot uses only its current perception to move and explore while avoiding collisions ([S1], [S2]); and (b) servo-ed navigation where the robot is given a pre-planned reference trajectory and uses some closed-loop control law to follow it [S7], [S6]. Servoed navigation approaches, can be further classified into state-space tracking [S5], [S4], and perception-space tracking [S8], [S3].

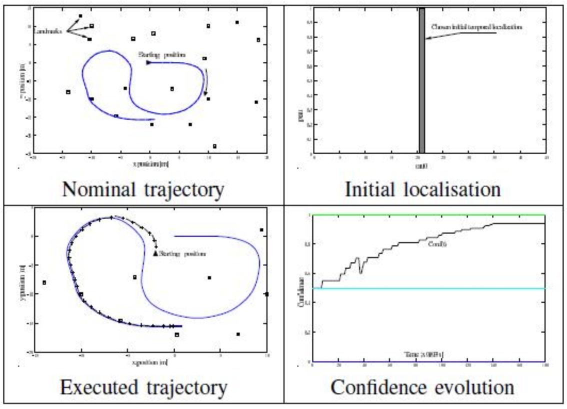
State-space tracking has two main requirements: first the reference trajectory must be described in the state space, and second, the robot must also be able to localize in the state space. Conversely, in perception-space tracking, the trajectory is defined with respect to local perception only, hence avoiding the need for global localization. A particular application of perception tracking is visual servoing, classically implemented as the convergence of observed image to a fixed reference image.

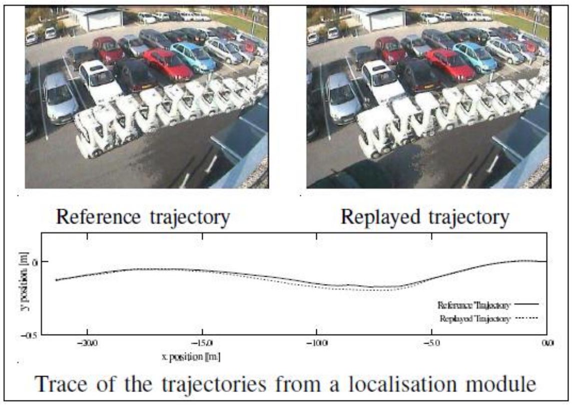
Given that significant work already exists for state-space tracking, in the context of the NOPTILUS project, we are particularly interested in perceptual tracking which is necessary when the AUVs navigate in parts of the environment where absolute positioning information is unavailable or very poor. For this challenging scenario, we consider the case where: i) a reference trajectory is defined as a sequence of observations perceived by an onboard sensor (sonar and/or video) along the robot's motion direction; and ii) no localization system is available to perform position tracking. This situation is interesting for at least three reasons: i) since trajectory is not geo-referenced, we do not need to deal with the complex task of global localization; ii) this form of trajectory can be naturally and easily learned from examples; and iii) such an approach has a biological motivation as it is similar to mechanisms that animals use for memorizing and representing paths.

In the context of NOPTILUS, we seek to endow AUVs with the ability to follow any sensory-motor trajectory, as long as the robot starts in its neighborhood. We divide this objective in three tasks:

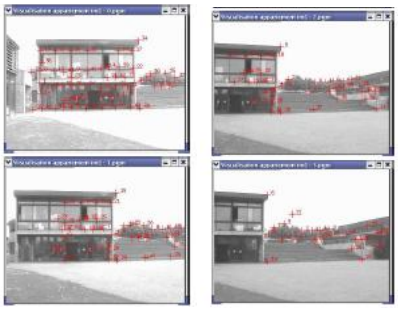
- **Initialization:** Given a sensory-motor trajectory Tsm, and an observation O, what is the robot temporal position $\tau(0)$? In other words, to the AUV must find the *$\tau(0)$ in [0,t1]* for which O is closest to Tsm($\tau(0)$). Note that this does not guarantee that O is an observation on Tsm.
- **Tracking:** Given Tsm, O, and an estimate τ (t) of the robot's temporal position at time t, for the AUV must compute the motion-control commands which lead to a replay of Tsm. This implies that the robot should be able to track τ along the trajectory.

- **Self-diagnosis**: Given Tsm, O, and τ (t), we want the system to determine whether the hypotheses on which the current behavior is built on are still valid. This means that the system should compute an estimate of its self-confidence over time. Special care will be taken when defining self-confidence since the overall system reliability hinges on the UAV's ability to identify when it veers off track.





Examples of sensory-motor trajectory replays have been presented in [S9]. These results used an autonomous car, with a 2D laser scanner and artificial landmarks in the environment. In order to manage uncertainties such as occluded landmarks or excessive observations, a probabilistic framework was used. The final framework included initialization of the replay, trajectory tracking, confidence estimation, and obstacle avoidance. Another example of sensory-motor trajectory tracking is presented in [S10]. In this case, image-based visual servoing is used to follow a sequence of images through the environment. In this work, localization was based on points of interest detected in the image sequence but does not include a specific framework to manage uncertainties. Moreover, this control is based on visual servoing and does not include obstacle avoidance.



Progress beyond the state of the art

As compared to existing approaches, the NOPTILUS will have to address three main challenges:

1) The trajectory-tracking system will have to use either only sonar or a combination of sonar and active vision to define the trajectory and localize the system with respect to it. The use of sonar with natural landmarks is likely to introduce a lot of uncertainty in the localization. The proper modeling of these uncertainties will require a strong collaboration with the NOPTILUS methodologies for Situation Understanding (objective (O1)).
2) Tracking the reference trajectory in the presence of currents will be significantly more challenging for an AUV as compared to a car-like robot. Thus, it will be necessary to introduce a model of the system's dynamics in the control framework, while still accounting for possible obstacles. This aspect will require tight integration with the NOPTILUS Motion Control Design.
3) The self-diagnosis presented in [S9] is not directly applicable to systems that rely on imprecise sonar sensors for perceiving their underwater environment. Thus, additional effort will have to be devoted to monitoring the quality of the trajectory tracking. In particular, when the system is initialized, several time indices in the sensory-motor trajectory could match the current observation. In this case, the system will need to actively choose to move until it gathers sufficient information about its correct spatio-temporal localization. To address all these issues, significant advances in the areas of active localization and performance monitoring will be core contributions of the NOPTILUS project.

B1.2.8 Situation Understanding

Human operators in current multi-AUV systems contribute not only their maneuvering and recognition skills, but also their high-level cognitive abilities for understanding the situation in the environment the AUVs operate in. Since the main objective of the NOPTILUS project is to offer a fully-autonomous multi-AUV system, it is important to develop methods and techniques for high-level sensor fusion, recognition in timed data, event detection, and event prediction. We use the term "situation understanding" to refer to all these cognitive abilities for inferring high-level representations of the situation at hand. This is perhaps one of the most difficult aspects of the proposed project and the first barrier towards true autonomy compared to the current state-of-the-art. Its importance can be stretched by the fact that high-level decision making for near-optimal planning and task assignment towards successful mission completion cannot be achieved without a high-level understanding of the situation in the surrounding environment.

Each AUV in the system is equipped with a variety of sensors providing continuous low-level data which are filtered and processed to provide information which can then be shared among all vehicles. In that sense, the entire team of the AUVs constitutes a sensor network with a dynamically changing topology. Building on the information provided with respect to the current formation, the AUVs can share measurements with what, where, and when labels; i.e., share each observation, its sampling time and location, as well as its possible attributes. Fusing this stream of information in order to create a "clear and complete picture" is the first step towards realizing the NOPTILUS system; "Cooperative Distributed Estimation for Map Creation and Process Tracking" Module (see section B1.2.5) responsible for completing such a task.

The next step is to recognize sequences of interest in this stream of information which may signal the presence or the initiation of a particular event. Finally, the last step is to infer possible evolutions of an on-going event and use this prediction to assist decision making. In other words, there is a need for devising methods which

- Based on all available measurements and information provided about the type, location, etc of the mission;

- Need to "recognize dynamic events" in order to update the NOPTILUS assignment, planning and navigation module

Examples of such – dynamic – events include AUV being inside an oil spill, faulty/unstable AUV behavior, AUV getting caught on a fishing net, seaweed tangled on propeller, strong opposing current not allowing AUV to enter an area, thermal gradient, severe coupling of the dynamics due to other AUVs or nearby objects, etc. In cases such events are present, an efficient and autonomous multi-AUV system should be capable of recognizing the presence (and type) of such events and update its automatic trajectory generation system accordingly so that it achieves its operational goal (e.g. that of mapping and detecting/tracking dynamic processes) subject to the constraint of the presence of the event (e.g. subject to the constraint that one of the AUVs is not able to track accurately a trajectory due to seaweed tangled on its propeller or strong opposing currents not allowing it to enter an area).

As there are no well-established practical methodologies or theoretically sound algorithms for recognizing dynamic underwater events like the ones mentioned above, the approach within NOPTILUS is to use data from past missions (a rich amount of them is already available at the Test Case) to learn how to recognize such events. Please note that as the development of the NOPTILUS methodology for recognizing dynamic events will be based on a "learning-from-past-data" approach, the efficiency of this methodology will strongly depend on the availability of past data. As a result, in cases where no "rich" past data are available or in case of unforeseen events, the NOPTILUS methodology for recognizing dynamic events will not be always possible to recognize dynamic events in which case human intervention will be required. However, most of the events identified so far are common to all underwater missions and a rich amount of past data is available for such events. Moreover, even in the case where human intervention will be required, such an intervention will be "minimum" and no advanced and complicated human actions will be required that vitiate the fully-autonomous nature of NOPTILUS.

Within NOPTILUS, machine learning methodologies, reinforcement learning tools, and probabilistic context-free grammars will be exploited in innovative ways and will be combined with a rich set of experimental observation logs from human-operated underwater missions, in order to develop all necessary methodological and algorithmic tools for accomplishing the aforementioned steps. All these methodological and algorithmic steps are detailed in the description of Work Package 6.

B1.2.9 Optimal Planning, Assignment and Navigation

Designing, in real-time, the motion strategy for a team of AUVs performing a situation awareness operation is probably the most complicated and challenging issue in multi-AUV applications. Given the system's limited recourses, the presence of various obstacles, as well as localization and sensing constraints, the problem at hand is to Plan, Assign and Navigate (PAN) – in real-time – the AUVs so that the information acquired by their sensors is maximized and the particular situation awareness operation is successfully accomplished as fast as possible. The fact that there are many possible decisions that can be made at each time-instant (even for single-AUV systems) makes the overall problem extremely challenging even in the ideal case where the external environment (e.g. location of obstacles, etc) and its interactions with the AUVs are perfectly known. As expected, the problem becomes immensely more complicated when the multi-AUV system operates in highly uncertain and/or rapidly changing environments as is the case in most real-world situations.

The majority of existing approaches employ either heuristic approaches which, suffer from the same drawbacks as humanly-operated multi-robot systems, or optimization-based approaches which are based on relaxations of highly-nonlinear (and often NP-complete) optimization problems, see [O1]-[O13] for an indicative list. Both methods can lead to very poor overall system performance (e.g. during mapping, several areas of interest may not be visited at all, while in dynamic-process tracking applications the vehicles may lose track of the process/target) which has hindered their applicability to real-world multi-robot systems. An alternative to the aforementioned approaches is the so-called *cognitive-based or learning ones*, see e.g. [O14]-[O22], where a motion strategy design, with the ability to “recognize its mistakes and learn from them”, is repeatedly exposed to situation-awareness examples until it learns to efficiently cope with such operations. Such an iterative learning procedure is time-consuming and often difficult to realize in practice. Thus, in many cases simulated versions of the actual environments are employed to “replicate” the actual ones. Although such cognitive/learning methods conceptually could provide efficient multi-AUV PAN, this unfortunately is not the case: there is no guarantee that the overall approach will perform efficiently when deployed in environments even slightly different than the ones it has been trained for. For all these reasons, cognitive/learning approaches, although have been successfully applied to many robotic applications, have only had limited applicability in AUV situation-awareness operations.

As part of the FP7 sFLY project (swarm of flying micro-air-vehicles, www.sfly.org), one of the NOPTILUS partners has recently introduced an alternative to existing cognitive/learning approaches for PAN in situation awareness applications. By employing a – scalable – switching set of linear decision-making mechanisms, the approach of [O23]-[O25] achieves to formulate the optimal[4] real-time motion strategy design as a convex optimization problem. Contrary to cognitive/learning approaches, the design of [O23]-[O25] does not require the time-consuming repetition of simulations or real-world experiments. Instead it efficiently solves a convex optimization problem which can be done very fast and in real-time even when the number of vehicles involved is large.

Although the approach of [O23]-[O25] can potentially offer an efficient solution for NOPTILUS’s motion strategy design, several significant enhancements and improvements are required in order to achieve this objective. All these methodological steps are detailed in the description of Work Package 7.

[4] More accurately: the problem of arbitrarily-close-to-optimal real-time motion strategy design.

B1.3 S/T Methodology and Associated Work Plan

B1.3.1 OVERALL STRATEGY OF THE WORK PLAN

NOPTILUS comprises 9 Work-Packages (WP), each consisting of several tasks. The project is organized along 7 technical work packages, one of them dedicated to integration and evaluation, and 2 work packages for management and dissemination, respectively. Each partner takes on one side the responsibility for his research topic, but is also strongly involved in the integration, demonstration and evaluation of the overall system. The common research platform (multi-AUV system) and the integrated demonstrations guarantee a strong interaction and collaboration between the partners.

The overall duration of NOPTILUS is scheduled for 4 years (48 months) and is divided in 4 main stages (see Gantt chart in Section B1.3.2):

- Development and design of the individual methodological and algorithmic components and elements addressing the low-level NOPTILUS objectives (i.e. related to communications, sensing, and localization) as well as definition and specification of all hardware components of the NOPTILUS system (WP2 and WP3).
- Development and design of all methodological and algorithmic components and elements addressing the medium-level NOPTILUS objectives (WP4 and WP5).
- Development and design of all methodological and algorithmic components and elements addressing the high-level NOPTILUS objectives (WP6 and WP7).
- Integration, demonstration and evaluation of the overall NOPTILUS system (WP8).

Project management and dissemination, training and exploitation activities (WP1 and WP9) constitute a continuous phase that is active during the whole project life.

The first 3 of the above stages end with an **integration week** and are managed along a list of milestones and deliverables. The integration weeks assemble the key project engineers at the Test Case location for 2-3 weeks. The main objective of these meetings is to integrate and test all elements, track progress, identify and resolve potential problems, and define the next phase in more detail. Moreover, these meetings help to integrate the team and their developed technologies, and serve as the main points of reference for the progress of the project. In addition to the integration weeks involving all partners, individual integration will be realized by exchange of PhD students and semester-long visits of individual partners. Furthermore, CERTH will have a **technical project manager** that will regularly (at least once every year) visit each partner's lab and discuss all upcoming issues. These measures will ensure the alignment of the whole consortium to the common overall objective and should guarantee the success of the project.

The demonstration period will start immediately after integration week 3 (where all pieces of the integrated NOPTILUS system will be brought together, integrated and verified) and will last for a 6 month-period. The timing of the integration weeks and the demonstration period is shown bellow.

Timing of Integration Weeks and Demonstration Period			
Integration Week 1	Integration Week 2	Integration Week 3	Demonstration Period
M18	**M30**	**M42**	**M43-M48**

B1.3.2 TIMING OF WORKPACKAGES

ID	Work Package	Task Name	Start	Finish
1	**WP 1**	**Project Management**	01/04/2011	31/03/2015
2	**1.1**	Strategic Management	01/04/2011	31/03/2015
3	**1.2**	Technical Management	01/04/2011	31/03/2015
4	**1.3**	Administrative and Contractual Management	01/04/2011	31/03/2015
5	**WP 2**	**System Components**	01/04/2011	31/03/2014
6	2.1	System Specification	01/04/2011	28/09/2011
7	2.2	Gateway buoys and moored sensors	01/04/2011	29/03/2012
8	2.3	Command centre	01/11/2011	30/10/2012
9	2.4	AUV hardware and software upgrades	02/04/2012	27/09/2013
10	2.5	ASV hardware and software upgrades	02/04/2012	29/03/2013
11	2.6	Logistic facilities at harbour	01/11/2011	01/05/2014
12	**WP 3**	**Communications, Sensing and Localization**	04/04/2011	27/09/2013
13	3.1	Underwater Communications	04/04/2011	28/09/2012
14	3.2	Underwater Vision	04/04/2011	01/04/2013
15	3.3	Cooperative Underwater Localization	04/04/2011	28/09/2012
16	3.4	Collaborative Underwater Sensing	04/04/2011	28/09/2012
17	3.5	Sonar/Image Fusion and Interfacing with Control Modules	01/11/2011	29/10/2013
18	**WP 4**	**Cooperative Distributed Estimation**	01/11/2011	29/10/2013
19	4.1	Cooperative Mapping	01/11/2011	29/10/2013
20	4.2	Cooperative Process Tracking	02/04/2012	27/09/2013
21	**WP 5**	**Motion and Sensory-Motor Control**	01/11/2011	29/10/2013
22	5.1	Motion Control	01/11/2011	29/10/2013
23	5.2	Sensory-Motor Control	01/11/2011	29/10/2013
24	5.3	Motion/Sensory-Motor Control Switching Mechanism	01/04/2013	26/09/2013
25	**WP 6**	**Situation Understanding**	01/11/2011	29/10/2014
26	6.1	Learning from Past Data Design	01/11/2011	01/05/2014
27	6.2	Learning Structured Prediction	01/11/2011	01/05/2014
28	6.3	Combining Grammars and Structured Prediction	01/04/2013	26/09/2014
29	**WP 7**	**Optimal Planning, Assignment and Navigation**	01/11/2011	29/10/2014
30	7.1	Arbitrarily-close-to-optimal, Scalable multi-AUV Motion Strategies	01/11/2011	29/10/2013
31	7.2	Real-time Cognitive-based Adaptive Re-design of Motion Strategies	02/11/2012	05/05/2014
32	7.3	Incorporating Collaborative Communication and Sensing Requirements and Physical, Communication and Processing Constraints	01/11/2013	31/10/2014
33	7.4	Interfacing with the other NOPTILUS Modules	01/04/2014	26/09/2014
34	**WP 8**	**System Integration and Evaluation**	04/04/2011	01/04/2015
35	8.1	Development of evaluation methodology	04/04/2011	30/03/2012
36	8.2	Integration of fixed components	01/11/2011	01/05/2013
37	8.3	AUV system's integration	01/04/2013	31/03/2014
38	8.4	ASV system's integration	02/11/2012	05/05/2014
39	8.5	Systems integration	04/11/2013	31/10/2014
40	8.6	Demonstration and Evaluation	03/11/2014	05/05/2015
41	**WP 9**	**Dissemination, Training and Exploitation**	04/04/2011	01/04/2015
42	9.1	Disseminantion	04/04/2011	01/04/2015
43	9.2	Training	04/04/2011	01/04/2015
44	9.3	Exploitation	04/04/2011	01/04/2015

Figure 2. NOPTILUS GANTT Chart

B1.3.3 EFFORTS FOR THE FULL DURATION OF THE PROJECT

WP	Task	Title	CERTH	FEUP	ETHZ	TU Delft	TSI	Imperial	MST	APDL	CNRS	TOTAL
1		Project Management	1.0	4.0	0.0	2.0	2.0	0.0	4.0	2.0	4.0	19.0
	1.1	Strategic Management	1.0	2.0	0.0	1.0	1.0	0.0	2.0	1.0	2.0	10.0
	1.2	Technical Management	0.0	2.0	0.0	1.0	1.0	0.0	2.0	1.0	2.0	9.0
	1.3	Administrative and Contractual Management	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2		System Components	1.0	25.0	0.0	4.0	3.0	5.0	28.0	9.0	0.0	75.0
	2.1	System Specification	0.0	3.0	0.0	0.0	0.0	0.0	3.0	2.0	0.0	8.0
	2.2	Gateway buoys and moored sensors	0.0	2.0	0.0	1.0	0.0	0.0	4.0	2.0	0.0	9.0
	2.3	Command centre	1.0	2.0	0.0	1.0	1.0	2.0	2.0	2.0	0.0	11.0
	2.4	AUV hardware and software upgrades	0.0	8.0	0.0	1.0	1.0	2.0	12.0	0.0	0.0	24.0
	2.5	ASV hardware and software upgrades	0.0	4.0	0.0	1.0	1.0	1.0	3.0	0.0	0.0	10.0
	2.6	Logistic facilities at harbour	0.0	6.0	0.0	0.0	0.0	0.0	4.0	3.0	0.0	13.0
3		Communications, Sensing and Localization	1.0	8.0	0.0	15.0	18.0	22.0	11.0	0.0	1.0	76.0
	3.1	Underwater Communications	0.0	2.0	0.0	10.0	0.0	0.0	3.0	0.0	0.0	15.0
	3.2	Underwater Vision	0.0	2.0	0.0	0.0	0.0	17.0	3.0	0.0	0.0	22.0
	3.3	Cooperative Underwater Localization	0.0	0.0	0.0	3.0	9.0	0.0	0.0	0.0	0.0	12.0
	3.4	Collaborative Underwater Sensing	0.0	2.0	0.0	2.0	8.0	0.0	2.0	0.0	0.0	14.0
	3.5	Sonar/Image Fusion and Interfacing with Control Modules	1.0	2.0	0.0	0.0	1.0	5.0	3.0	0.0	1.0	13.0
4		Cooperative Distributed Estimation	30.0	10.0	0.0	0.0	13.0	12.0	0.0	0.0	1.0	66.0
	4.1	Cooperative Mapping	14.0	5.0	0.0	0.0	7.0	6.0	0.0	0.0	1.0	33.0
	4.2	Cooperative Process Tracking	16.0	5.0	0.0	0.0	6.0	6.0	0.0	0.0	0.0	33.0
5		Motion and Sensory-Motor Control	10.9	6.0	14.4	0.0	0.0	1.0	6.0	0.0	14.0	52.3
	5.1	Motion Control	7.9	2.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	11.9
	5.2	Sensory-Motor Control	0.0	2.0	14.4	0.0	0.0	0.0	2.0	0.0	12.0	30.4
	5.3	Motion/Sensory-Motor Control Switching Mechanism	3.0	2.0	0.0	0.0	0.0	1.0	2.0	0.0	2.0	10.0
6		Situation Understanding	3.0	2.0	0.0	0.0	29.0	3.0	4.0	0.0	0.0	41.0
	6.1	Learning from Past Data Design	1.0	1.0	0.0	0.0	11.0	1.0	4.0	0.0	0.0	18.0
	6.2	Learning Structured Prediction	1.0	1.0	0.0	0.0	11.0	1.0	0.0	0.0	0.0	14.0
	6.3	Combining Grammars and Structured Prediction	1.0	0.0	0.0	0.0	7.0	1.0	0.0	0.0	0.0	9.0
7		Optimal Planning, Assignment and Navigation	38.0	9.0	0.0	4.0	8.0	3.0	6.0	0.0	0.0	68.0
	7.1	Arbitrarily-close-to-optimal, Scalable multi-AUV Motion Strategies	16.0	3.0	0.0	1.0	3.0	1.0	0.0	0.0	0.0	24.0
	7.2	Real-time Cognitive-based Adaptive Re-design of Motion Strategie	13.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.0
	7.3	Incorporating Collaborative Communication and Sensing Requirements and Physical, Communication and Processing Constraints	5.0	4.0	0.0	2.0	3.0	2.0	4.0	0.0	0.0	20.0
	7.4	Interfacing with the other NOPTILUS Modules	4.0	2.0	0.0	1.0	2.0	0.0	2.0	0.0	0.0	11.0
8		System Integration and Evaluation	14.0	44.0	0.0	5.0	9.0	8.0	57.0	26.0	4.0	167.0
	8.1	Development of evaluation methodology	1.0	2.0	0.0	0.0	0.0	0.0	3.0	4.0	0.0	10.0
	8.2	Integration of fixed components	0.0	3.0	0.0	1.0	1.0	0.0	5.0	0.0	0.0	10.0
	8.3	AUV system’s integration	0.0	6.0	0.0	1.0	1.0	2.0	7.0	3.0	0.0	20.0
	8.4	ASV system’s integration	0.0	3.0	0.0	1.0	1.0	2.0	6.0	0.0	0.0	13.0
	8.5	Systems integration	5.0	14.0	0.0	1.0	2.0	2.0	14.0	2.0	1.0	41.0
	8.6	Demonstration and Evaluation	8.0	16.0	0.0	1.0	4.0	2.0	22.0	17.0	3.0	73.0
9		Dissemination, Training and Exploitation	3.0	6.0	0.0	3.0	5.0	3.0	6.0	3.0	3.0	32.0
	7.1	Disseminantion	1.0	2.0	0.0	1.0	2.0	1.0	2.0	1.0	1.0	11.0
	7.2	Training	1.0	2.0	0.0	1.0	1.0	1.0	2.0	1.0	1.0	10.0
	7.3	Exploitation	1.0	2.0	0.0	1.0	2.0	1.0	2.0	1.0	1.0	11.0
		TOTAL	101.9	114.0	14.4	33.0	87.0	57.0	122.0	40.0	27.0	596.3

B2. IMPLEMENTATION

B2.1 Management structure and procedures

The management structure of the NOPTILUS project has been organized to separate scientific management from administrative tasks, with a double objective of ***a) strong scientific management*** and ***b) effective interactions between WPs***.

B2.1.1 OVERVIEW OF THE NOPTILUS PROJECT STRUCTURE

The ambitious objectives of NOPTILUS require a strong and coherent management structure and organization, able to support the various tasks of the project and take the appropriate decisions on strategic orientations. The management structure is split into three levels of management as shown in Figure 2:

- The strategic management is based on the principles of the European Foundation for Quality Management.
- The integrative management is based on the principles developed in the ISO10006 standard.
- The WP management is based on the processes and procedures implemented by the Management Board (MB), which will be the basis and the tool for the successful NOPTILUS management and integration.

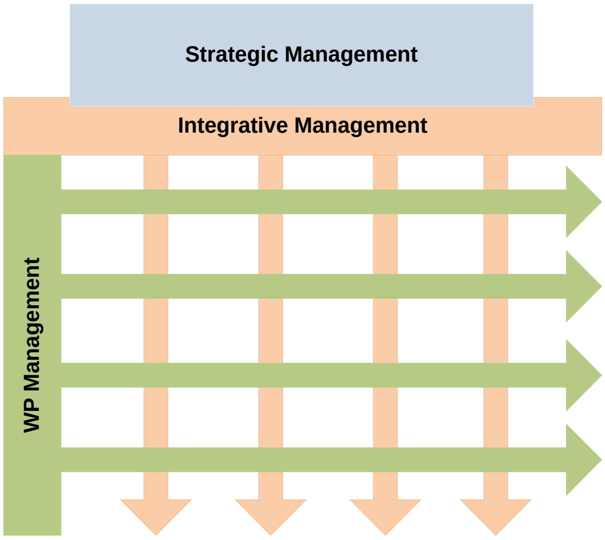


Figure 2. *NOPTILUS* management levels.

All levels of decision and action, including management of WPs, follow the continuous process improvement principle towards Excellence represented by the Deming or the PDCA (Plan Do Check Act) wheel. The MB, made up by the WP leaders, will be set up at the beginning of the project life and will be coordinated by CERTH that will implement and deploy the necessary management procedures (costs, people, facilities, communication, knowledge, purchase, legal aspects and IPR, risks). The structure and organization of management activities are presented in Figure 3. A matrix organization has been adopted in order to provide more flexibility and adaptability in changing conditions. The matrix organization takes advantage of the benefits of a pure-project organization while maintaining the advantages of the functional organizations. The NOPTILUS organizational structure is composed of seven WPs (WPs 2 to 8). Two additional WPs (1 & 9) are especially dedicated to the project management (WP1) and dissemination, training and exploitation (WP9) thus ensuring that NOPTILUS has a solid management and flexible structure adapted to its ambitious context.

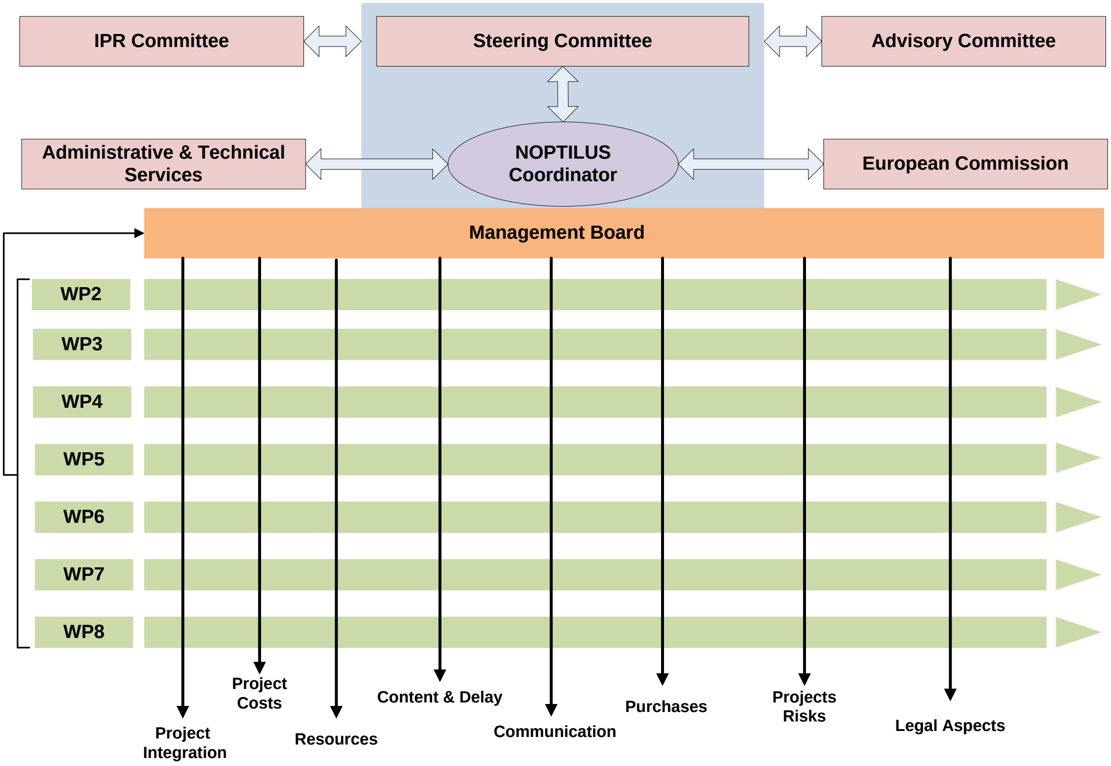


Figure 3. *NOPTILUS* management structure and organization

B2.1.2 The Strategic Management

The strategic management level includes the main decision-making role: The ***Steering Committee (SC)***, the ***Management Board (MB)*** and the NOPTILUS ***Project Coordinator (PC)***. The coordinator will be assisted by the ***Advisory Committee (AC)*** and ***Intellectual Property Right Committee (IPRC)***, as shown in Figure 3. The structure of the MB has been already discussed; the SC, PC, AC and IPRC are as:

- **Steering Committee**: The SC will be made up of high level representatives of each partner. The SC approves every major decision concerning the project (e.g. budget and financial contribution of the EC among the consortium partners). Its main role will consist of overseeing the integration of the partners' activities and taking high-level decisions in each partner organization with a view to adapting management structures and accelerating integration. It will make sure that the strategy adopted is appropriate to meet the expected results. The SC will meet every year or more often when required. The SC chairperson will be elected among the members of the SC by unanimous decision of the representatives. The SC will be assisted in its tasks by the AC (Figure 3). All the arrangements of the SC shall be stated in the Consortium Agreement prior to the project beginning.
- **NOPTILUS Project Coordinator**: The PC (Associate Prof. Elias Kosmatopoulos, CERTH) is going to coordinate the NOPTILUS project. He is in charge of the global consortium organization and leads the MB that guarantees that the management structure works to allow a follow-up and communication between partners and to perform all the tasks described in the EC Grant. He will be the sole interface between the consortium and the EC and will coordinate

the upwards and downwards communication between partners within the project. He will be supported by WP Leaders (MB) in the implementation of management procedures (costs, people, facilities, communication, knowledge, purchase, legal aspects and IPR, risks). The PC is also responsible for strategic aspects' implementation and for every day NOPTILUS's management monitoring. The PC will be assisted by the **Project Administrative Officer** (Dr. Agni Karadimou), who will take care of administrative and financial issues of the project and will ensure collection and timely delivery of the deliverables, financial statements and project reports; and the **Technical Project Manager** (Dr. Savvas Chatzichristofis) who will be responsible for the technical and scientific coordination and supervision of the work packages, planning and control of activities and preparation of deliverables.

- **Advisory Committee**: The AC consists of three external experts recognized for their expertise in the field of the project who will be appointed by the SC. The AC is a scientific evaluation consultative body. It will advise the SC and MB on project orientations or special issues. It evaluates the scientific program of activities for the project as well as the results obtained. It may be consulted by the MB on any scientific issues.
- **Intellectual Property Right Committee**: The IPRC is composed of one specialist of each NOPTILUS partner Organization. The IPRC will set up a quality and monitoring procedure to manage the protection of IPR-issues. The IPRC will work in close relation to IPR-Helpdesk of the EC and will assist the consortium in the implementation of measures in connection with publications and protection of knowledge and their dissemination.

B2.1.3 THE INTEGRATIVE MANAGEMENT

The MB will perform the integrative management supported by the Administrative Service. The MB represents the operational decision level within the NOPTILUS management organization. According to the strategy decided by the SC, the MB makes decisions regarding the management and the project's coordination. More precisely, the operational level within the NOPTILUS management organization is performed by the PC and the WP Leaders. These persons make decisions regarding the technical and management issues including implementing the overall project strategy fixed by the SC (e.g. project re-organisation, contractual matters, IPR, dissemination, exploitation). The MB will meet at least once every six months or more often (***Progress Meetings***) when required under the chairing of the PC. It will inform the SC on the progress of the NOPTILUS project. The MB is the structure through which the day-to-day operational management of the different management processes is implemented. The MB is responsible for deploying the necessary procedures and the planning, monitoring and controlling the actions to make sure that the different WPs are well consolidated. The MB will monitor and manage the project according to all requirements given to the call. The MB will:

- *Implement* and *improve the management procedures* and monitoring progress according the ISO 10006 international management standards.
- *Manage the administrative, legal, financial, communication, knowledge* and other non-technical aspects (Figure 3).
- *Assist* the SC in the project's steering (follow-up of planning schedule, costs, task initiation or completion, etc.) and assist the PC in consolidation tasks and financial, IPR, ethic's follow-up.
- *Organize meetings*.

The ***Administrative and Technical Service (ATS)*** will be established within CERTH Administration Service in order to support the PC and the MB. It will consist of the Project Administrative Officer, the Technical Project Manager, a financial expert, a legal expert and secretarial/ administrative support. The responsibility of the ATS is to take care of keeping the project running according to decisions of the MB, the project plan and agreements, and to take care of all administrative, financial, legal work related to the project.

B2.1.4 The WP Management

All NOPTILUS activities will be coordinated at the WP level by the WP Leaders. They are responsible for the detailed coordination, planning, monitoring and reporting of each WP and for the detailed communication with other WPs. More specifically the WP Leaders will be responsible for:

- Coordinating the WP Tasks including technical and management activities.
- Continuously monitoring the progress of the tasks, controlling its efficiency.
- Forwarding a synthesis of WP activities to the NOPTILUS dissemination channels (WP9).
- Ensuring that milestones and deliverables of the WPs are fulfilled.
- Organizing, if needed, special technical meetings to determine suitable measures to be taken.

The WP Leaders will provide all necessary information relating to administrative and reporting management to PC who will then consolidate it. Each WP Leader will manage the relevant WP according to the ISO 10006 project management principles. The PC will support WP Leaders in the implementation of management procedures. The WP Leaders have already been identified according to their expertise and are displayed in the following table.

Table 5. ***Work package leaders***

WP	WP Leader	Organization	Country
WP1	E. Kosmatopoulos	CERTH	GR
WP2	J. Borges de Sousa	FEUP	PT
WP3	A. Liavas	TSI	GR
WP4	L. Doitsidis	CERTH	GR
WP5	C. Pradalier	ETH Zurich - CNRS	CH/FR
WP6	M. Lagoudakis	TSI	GR
WP7	E. Kosmatopoulos	CERTH	GR
WP8	L. Madureira	MST	PT
WP9	F. Lobo Pereira	FEUP	PT

B2.1.5 NOPTILUS Test Case Management

Special attention will be given within NOPTILUS for the overall management of the NOPTILUS Test Case. For this reason a directly link and monthly communication will be established between the project coordinating team and the leaders of WP2 and WP9, responsible for the systems' specification, integration, functioning, demonstration and evaluation. Also, the technical manager of NOPTILUS will be visiting the Test Case premises, at least once every six months.

B2.1.6 All NOPTILUS Monitoring and Progress Reporting

Every six months, each WP Leader will submit to the PC a consolidated report on the progress of the different WP aspects. The reporting will include information about the technical progress, results obtained (e.g. deliverables), the compliance with the work programme and all the relevant information at management level (resources, costs, delays etc). The progress status of each task will also be reported in terms of percentage of completion, estimated time for completion, actual person-months spent and person-months needed to complete the task. The PC will synthesize the overall project status and planning. The PC will also update the bar chart and the person-power matrix using the data received from the partners. The following reports will be prepared by the MB and supplied by the PC:

- ***Biannual Progress Reports***: These reports, delivered every six months, will contain a concise description of all activities undertaken with respect the objectives, action and work plan envisaged in the project.
- ***Mid-term Report***: This report will be released in M24. It will contain a detailed account of the activities undertaken with respect the objectives, actions and work plan envisaged in the project during the first 24 months. For the mid-term assessment report presentation, the PC will organize a review meeting (Mid-term Project Review Meeting) with all partners and the Commission's representative. The purpose of this meeting will be to report on the progress to date and to redefine if necessary the program for the remaining part of the Grant Agreement.
- ***Final Report***: This report will contain a summary of the main achievements and results of the project; a detailed account of the activities undertaken with respect the objectives, actions and work plan envisaged in the project. It will be released at the end of the project and it will contain the following documents:
  - Biannual progress report of the last period;
  - Executive summary discussing achieved goals, evaluation of project against success criteria, lessons learned, envisaged follow-on.
  - The final statement of expenditure.
  - The final plan for the use and dissemination of foreground.
  - The report on awareness and wider societal implications.

For the final report presentation, the PC will organize a review meeting (***Final Project Review Meeting***) with all partners and the Commission's representative.

Finally, MST is to provide a very short progress report to the Project Officer after M3, M6 and thenceforth, unless indicated otherwise by the P.O., at six-monthly intervals, mentioning in particular any major changes in their resources (human and financial).

Project Reviews

Projects reviews (by the EC) will take place on Months 18, 30, 42 and 48 of the project. The location of the reviews is more likely to be the NOPTILUS test case location so that reviewers can check and evaluate the progress made to the NOPTILUS system.

Apart from the above-mentioned project reviews, a light technical review involving the Coordinator and the Project officer, and if need be one external expert, will take place at month 9 of the project. The Coordinator will provide an informal periodic activity report mentioning overall progress on the project workplan.

B2.1.7 Conflict Management

The basic approach is to resolve the conflicts at as low a level as possible. If this does not succeed, while going up the hierarchy, the main decision body is the MB. Figure 4 presents the basic conflict resolution procedure. Conflicts will be solved following internal WP procedures or in inter-WP meetings if needed. In case no solution is found at the WP level or at the inter-WP level or at IPRC, the issue is forwarded to the MB.

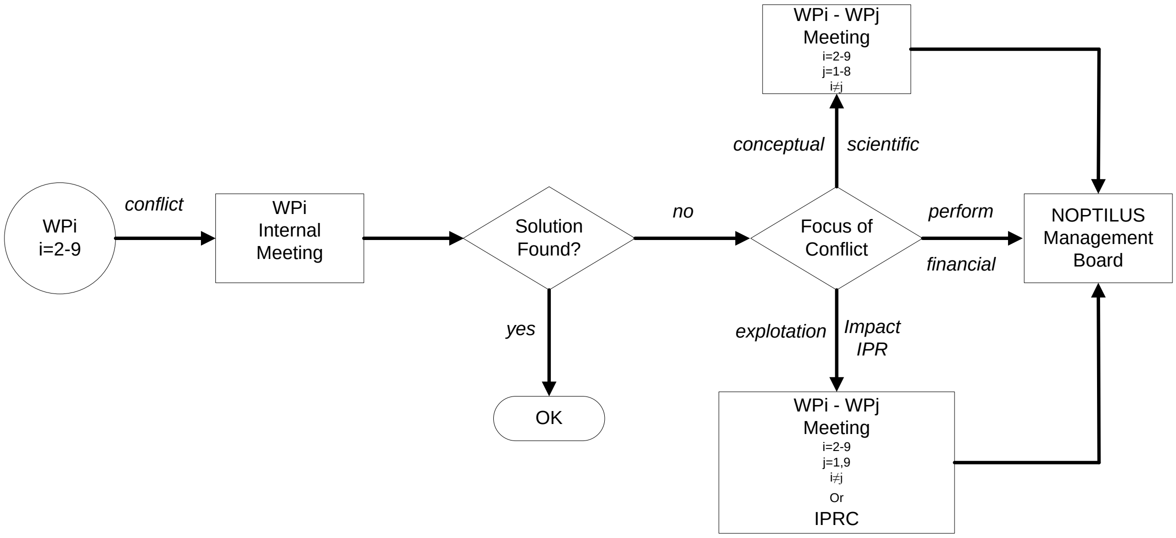


Figure 4. ***Conflict Resolution Procedure***

B2.1.8 RISKS AND OTHER CRITICAL FACTORS

The consortium has identified the factors that are critical to the final success of the project and defined methods and procedures to identify, assess, monitor and control areas of risk; see Appendix A for more details.

B2.1.9 CONSORTIUM AGREEMENT

A consortium agreement will be signed by all partners before the project starts and before the signature of the EC Model Grant Agreement. A preliminary version of the consortium agreement for the NOPTILUS project has been prepared and is under discussion by the consortium. The basic principles of this agreement concerning the structure of the management and the decision making procedures were presented in the previous section. Moreover, it will refine all the management specific arrangements (quorum, voting principles, roles, decision making process, definition of property rights, etc.) of the project consortium and will serve as the basis for the final negotiations before the Grant Agreement signature with the EC. In addition, the knowledge protection and IPR principles presented in this consortium agreement are also discussed in the next Section. All partners have expressed their commitment to reach an agreement on this preliminary version and to sign it before the EC Grant Agreement is signed, should the NOPTILUS proposal be selected for funding.

B2.1.10 INTELLECTUAL PROPERTY HANDLING AND CONFIDENTIALITY

NOPTILUS is given special emphasis on IPR issues. For this reason, it will set up from day one of the project, the IPR-Committee (see Section B2.1.2) that will assist the PC on IPR-related issues. IPR-related issues are presented in more detail in Section B3.

B2.2 Beneficiaries

B2.2.1. CERTH – Centre for Research and Technology – Hellas

www.iti.gr

The **Informatics and Telematics Institute (ITI)** of the **Centre for Research and Technology – Hellas (CERTH)** was founded in 1998 as a non-profit organization under the auspices of the General Secretarial of Research and Technology of Greece, with its head office located in Thessaloniki, Greece. Since 10.3.2000 it is a founding member of the Centre of Research and Technology Hellas (CERTH) also supervised by the Greek Secretariat of Research and Technology. ITI-CERTH is one of the leading Institutions of Greece in the fields of Informatics, Telematics and Telecommunications, with long experience in numerous European and national R&D projects. ITI-CERTH has participated in more than 60 research projects funded by the European Commission (IST FP5-FP7) and more than 85 research projects funded by Greek National Research Programs and Consulting Subcontracts with the Private Sector (I&T Industry). Only in 2006, the Informatics and Telematics Institute attracted an income of 5.6 M€ from National and European competitive R&D projects. For the last 10 years, the publication record of ITI includes more than 150 scientific publications in international journals, more than 400 publications in conferences and 45 books and book chapters. The development of the infrastructure of ITI-CERTH was financed by the National Research fund EPET II with € 2.3 million in the period 1998-2000.
The particular team of CERTH that will carry the work within NOPTILUS and has profound knowledge and broad experience in intelligent and learning control and optimization systems and their practical application in real-life large-scale systems such as swarms of robots, intelligent traffic and transportation systems, and energy efficient systems control. Theoretical research activities resulted in the development of popular intelligent control & optimization methodologies. Moreover, applied research activities resulted in popular intelligent large-scale control and optimization systems with hundreds of implementations in Europe and worldwide.

Dr. Elias Kosmatopoulos, **the Project Coordinator,** received the Diploma, M.Sc. and Ph.D. degrees from the Technical University of Crete, Greece, in 1990, 1992, and 1995, respectively. He is currently an Associate Professor with the Department of Electrical & Computer Engineering, Democritus University of Thrace, Greece and a Senior Researcher with CERTH/ITI. He was an Assistant Professor with the Department of Production Engineering and Management, Technical University of Crete (TUC), Greece and a Research Assistant Professor and Research Associate Professor with the Department of Electrical Engineering-Systems, University of Southern California (USC) and a Postdoctoral Fellow with the Department of Electrical & Computer Engineering, University of Victoria, B.C., Canada. Dr. Kosmatopoulos' research interests are in the areas of neural networks and intelligent control. He is the author of over 40 journal papers and book chapters and over 80 conference publications, on intelligent and learning control and optimization techniques and their application to various areas such as traffic and transportation systems, process systems, energy efficient buildings, structural systems, and intelligent vehicles and robotics. Elias Kosmatopoulos is or has been involved (mostly as project leader or co-leader) in many EU-funded projects including: Optimization & Control for Traffic Systems (FP5: EYE IN THE SKY, SMART NETS, RHTYTHM; FP6: CONNECT, EURAMP; FP7: NEARCTIS); Energy and safety for traffic systems (FP6 IP COOPERS); Optimization & Control of Flying Robot Teams (FP7 sFLY); Control for Energy Positive Buildings (FP7 PEBBLE); Large-scale Self-tuneable and Re-configurable Control System Design (FP7 AGILE).

Dr. Lefteris Doitsidis, received his diploma degree from the Production Engineering and Management Department of the Technical University of Crete, Chania, Greece, in 2000. In 2002 he was awarded his M.Sc. degree in Production Systems and in 2008 he received his Ph.D. at the same department. From 2002 to 2008, he has been a researcher at the Intelligent Systems and Robotics Laboratory of the same department. From August 2003 to June 2004 he was a visiting scholar at the Department of Computer Science and Engineering, University of South Florida, FL, U.S.A. He was a member of the Center of Robot Assisted Search and Rescue. Beginning in 2004 he has been at the Department of Electronics, Technological Educational Institute of Crete where he is currently an Assistant Professor. His research interests lie in the areas of multirobot teams, design of novel robotic systems, autonomous operation and

navigation of unmanned vehicles. He is also active in the areas of fuzzy logic and evolutionary computation. He has a leading role been involved in the EU-funded projects sFLY, PEBBLE and AGILE.
Dr. Savvas A. Chatzichristofis, **the Technical Project Manager,** received the Diploma and the Ph.D. degrees both from the Department of Electrical and Computer Engineering, Democritus University of Thrace, Greece, in 2005 and 2010, respectively. Currently, he is a postdoctoral Researcher at Centre for Research and Technology Hellas (C.E.R.T.H.), Information Technology Institute (I.T.I.). His research interests lie in the areas of multirobot teams, Computer Vision and Robotics, Image Processing and Analysis and Pattern Recognition. Savvas A. Chatzichristofis has been involved in the following EU-funded projects: Optimization & Control of Flying Sensor Teams (FP7 sFLY); Large-scale Self-tuneable and Re-configurable Control System Design (FP7 AGILE).

B2.2.2. FEUP – Faculdade de Engenharia da Universidade do Porto

www.fe.up.pt

The research undertaken by the **Faculty of Engineering at Porto University (FEUP)** will be done at the **Underwater Systems and Technologies Laboratory** (LSTS), which is one of leading European laboratories in underwater robotics. Porto University is the largest university in Portugal and it is also a top choice for Portuguese higher education students.

The LSTS is an interdisciplinary research laboratory established in 1997 with researchers drawn from Electric and Computer and Mechanical Engineering and from Computer Science. The LSTS is specialized on the design, construction and operation of unmanned vehicles and on the development of tools and technologies for the deployment of networked vehicle and sensor systems. In 2006 The LSTS was awarded the BES national innovation prize for the design of Light Autonomous Underwater Vehicle (LAUV).

Currently the LSTS fleet includes eight autonomous underwater vehicles (evolutions of the LAUV), two remotely operated vehicles, one autonomous surface vehicle, four unmanned air vehicles and ten drifters. The LSTS has been demonstrating these vehicles and technologies in the Atlantic and Pacific oceans and also in rivers, in Portugal and the United States of America. These demonstrations include several world firsts: in 2006, an autonomous underwater rendezvous between the autonomous submarines Isurus and Aries from, respectively, the LSTS and the Naval Postgraduate School in Monterey CA; in 2007, cooperative sampling in the Sacramento river, California, with an autonomous submarine from the LSTS and drifters from the University of California at Berkeley.
The LSTS is currently developing three autonomous underwater vehicles for the Portuguese Navy under the Seacon project funded by the Portuguese Ministry of Defence and is leading, in cooperation with the Portuguese Air Force Academy, a seven-year national program, funded by the Portuguese Ministry of Defence, for the development of unmanned air vehicle systems. The LSTS is working with the Portuguese Task Force for the Extension of the Continental Shelf in the operation of the Deep Sea Remotely Operated Vehicle (ROV) Luso and is also developing a deep sea ROV under this cooperation.

The LSTS is currently participating in several FP6 and FP7 projects such as Xpress and Con4Coord and also on the European Network of Excellence Conet. For further information please visit www.fe.up.pt/~lsts.

Fernando Lobo Pereira is a Professor at the Department of Electrical Engineering at Porto University. Currently, he is Director of Institute for Systems and Robotics - Porto and leader of the Automation, Control and Industrial Production Systems area of the Electrical and Computer Engineering Department of FEUP. He received the Ph.D. in Control Theory from Imperial College of Science and Technology, University of London in 1986. His research interests include control, dynamic optimization, impulsive systems, coordination and control of multiple dynamic systems, autonomous systems as well as control applications in mobile robotics and manufacturing systems. He participated in ca 40 R & D projects funded by the FCT (Portuguese government), EU and NATO and other agencies and addressing control theory - impulsive control, hybrid systems and dynamic optimization - and its application to design and operation of advanced systems requiring the coordinated control of multiple autonomous or tele-operated vehicles and other devices. He (co)-authored more than 250 publications.

João Borges de Sousa is a lecturer at the Electrical and Computer Engineering Department at Porto University in Portugal and the director of the Underwater Systems and Technologies (LSTS) Laboratory at Porto University. He received the M. Sc. degree in Electrical and Computer Engineering from Porto University in 1992. He did his Ph.D. studies under the supervision of Prof. Pravin Varaiya from the University of California at Berkeley. His research interests include unmanned vehicle systems, networked control, control and coordination of multiple dynamic systems, hybrid systems, systems engineering, and control architectures for multi-vehicle systems. Since 1997 he has been leading the design, implementation and deployment of advanced unmanned vehicle systems in projects funded by the Portuguese Foundation for Science and Technology, Nato and the EU, in Europe, and by ONR and DARPA in

the US. In 2006 he received the national BES Innovation National Award for the design of the Light Autonomous Underwater Vehicle. In 2007 he received an outstanding teaching award from Porto University. He authored more than 190 publications, including 20 journal papers.
P.B. Sujit received the B.E degree in electrical engineering from Bangalore University, Bangalore, India, in 1998, the M.Tech degree in Power Electronics from Visvesvaraya Technological University, Belgaum, India, in 2002, and the PhD degree in aerospace engineering from the Indian Institute of Science, Bangalore, India, in 2006. He was a post-doctoral fellow at Brigham Young University, Utah from 2006-2008 and since then he is working as a Research Scientist in the department of electrical engineering, University of Porto, Portugal. His primary research interests are in cooperative control of unmanned vehicles, path planning, task allocation and vision based systems.

B2.2.3. ETH Zurich – Autonomous Systems Laboratory, ETH Zürich, Switzerland

www.asl.ethz.ch

The Autonomous Systems Lab (ASL) at the Eidgenössische Technische Hochschule Zurich ETH Zurich (until June 2006 at EPFL Lausanne (http://asl.epfl.ch/)) is an internationally renowned research lab in the field of autonomous robot design and navigation. It has a large experience in the design and autonomous navigation of wheeled and flying autonomous robots for different kinds of environments and has recently started to explore the field of Autonomous Surface Vessels (ASV). Among recent results are personal robots with multi-modal interaction capabilities, wheeled locomotion systems that passively adapt to rough terrain, autonomous micro-aircrafts and autonomous cars with 3D navigation and mapping capabilities in rough terrains. Apart systems design, a major research focuses are in cognitive maps, feature based simultaneous localization and mapping (SLAM) using multiple modalities and path planning in highly dynamic environments. The Autonomous Systems Lab consists of around 45 researchers and application engineers and is involved in various National, European and ESA projects. Technology transfer is mainly realized through spin-off companies. The collaborators of the Lab have started eight new companies during the last 9 years covering the fields of personal communicators for conferences up to autonomous mobile robots for industrial applications and autonomous micro-helicopter. The expertise relevant to the PROJECT project is the Lab's robot design experience and especially the large competence in simultaneous localization and mapping (SLAM), hybrid and hierarchical representation of the environment and navigation in dynamic environments. The ASL team was responsible of the development and operation of 11 mobile tour-guide robots during the Swiss national exhibition expo.02. The Lab is also involved in the ExoMars project of the European Space Agency (ESA), in inspection robotics for power plant applications and autonomous cars. ASL is and was involved in many European projects and is currently leading the EU project SFLY (Swarm of Micro Flying Robots). In the context of student projects, the ASL has recently designed an autonomous sailing boat with the objective to realize the first autonomous crossing of the Atlantic Ocean and an autonomous boat for monitoring the algal populations of lakes. The ASL is also currently developing a high speed sailing boat using the hydrofoil technology. In 2009, the ASL developed the NARO underwater robot, whose structure and propulsion is inspired from tuna fish.

Roland Siegwart (ETH Zurich) is a full professor for autonomous systems at ETH Zurich since July 2006 and the Vice-President for Research of ETH Zürich since January 2010. He has a Diploma in Mechanical Engineering (1983) and Ph.D. in Mechatronics (1989) from ETH Zurich. In 1989/90 he spent one year as postdoctoral fellow at Stanford University. After that he worked part time as R&D director at MECOS Traxler AG and as lecturer and deputy head at the Institute of Robotics, ETH Zürich. In 1996 he was appointed as associate and later full professor for autonomous microsystems and robots at the Ecole Polytechnique Fédérale de Lausanne (EPFL). During his period at EPFL he was co-initiator and founding Chairman of Space Center EPFL and Vice Dean of the School of Engineering. In 2005 he held a visiting position at NASA Ames and Stanford University. Roland Siegwart is member of the Swiss Academy of Engineering Sciences and board member of the European Network of Robotics (EURON). He served as Vice President for Technical Activities (2004/05) and is currently Distinguished Lecturer (2006/07) and AdCom Member (2007- 2009) of the IEEE Robotics and Automation Society. He is member of the “Bewilligungsausschuss Exzellenzinitiative” of the “Deutsche Forschungsgemeinschaft (DFG)”. He is currently the coordinator of one European projects and co-founder of several spin-off companies.

Cedric Pradalier (ETH Zurich) Since November 2007, C. Pradalier is deputy director in the Autonomous Systems Laboratory at the ETH Zurich. He is the technical coordinator of various European Space Agency (ESA) funded projects (e.g. ExoMars Chassis and Locomotion) and of two European projects (Robots@Home, 2007-2010 and Nifti, 2010-2014). He is also involved in the development of innovative robotic platforms such as the autonomous sailing boat *Avalon*. He is a founding member of the ETH startup Skybotix, within which he is responsible for software development and integration. From 2004 to 2007, C. Pradalier was a research scientist at the CSIRO, Australia. He was then responsible with the development of software for the autonomy of large industrial robots and an autonomous

underwater Vehicle. The latter developed and used for researches about corals of the Great Barrier Reef, Australia.

B2.2.4. TU DELFT – DELFT UNIVERSITY OF TECHNOLOGY

www.tudelft.nl

The research area of the **Circuits and Systems group** of the **Delft University of Technology** covers the theory and applications of circuits and systems, signal processing, and VLSI circuit and system design methodology. The complexity of electronic circuits is ever increasing, and so is their design. Two drivers are (i) already phenomenal integration densities are still doubling every 18 months (Moore's law), and (ii) new advanced applications require integrated solutions with increased intelligence and immense processing power. The main goal in our research program is to provide a sound mathematical framework for synthesis and analysis problems in the complete trajectory from system application, algorithm design, mapping to a hardware architecture or embedded system, VLSI circuit design, and finally the design verification. Our system applications are taken from several areas that require new mathematical insights, e.g. wireless communications, underwater acoustic communications, distributed networks, radio astronomy and biomedical applications, and we limit ourselves to the central signal processing aspects of these. The objective is to develop efficient signal processing algorithms and to compile these onto embedded systems and the underlying physical circuits. The new insights are incorporated in design tools and actual designs. The group participates in DIMES and NIRICT, the Netherlands Institute for Research in ICT (an institute in the context of the 3TU Federation of the three Technical Universities in The Netherlands). Organizationally, the group is embedded in the Department of Micro-electronics and Computer Engineering of the Faculty of Electrical Engineering, Mathematics, and Computer Science (EWI).

Dr. Geert Leus received the electrical engineering degree and the PhD degree in applied sciences from the Katholieke Universiteit Leuven, Belgium, in June 1996 and May 2000, respectively. He has been a Research Assistant and a Postdoctoral Fellow of the Fund for Scientific Research - Flanders, Belgium, from October 1996 till September 2003. During that period, Geert Leus was affiliated with the Electrical Engineering Department of the Katholieke Universiteit Leuven, Belgium. Currently, Geert Leus is an Associate Professor at the Faculty of Electrical Engineering, Mathematics and Computer Science of the Delft University of Technology, The Netherlands. During the summer of 1998, he visited Stanford University, and from March 2001 till May 2002 he was a Visiting Researcher and Lecturer at the University of Minnesota. His research interests are in the area of signal processing for communications. Geert Leus received a 2002 IEEE Signal Processing Society Young Author Best Paper Award and a 2005 IEEE Signal Processing Society Best Paper Award. He is the Chair of the IEEE Signal Processing for Communications Technical Committee, and an Associate Editor for the IEEE Transactions on Signal Processing and the EURASIP Journal on Applied Signal Processing. In the past, he has served on the Editorial Board of the IEEE Signal Processing Letters and the IEEE Transactions on Wireless Communications.

B2.2.5. TSI – Telecommunication Systems Institute at the Technical University of Crete

www.tsi.gr

The Telecommunication Systems Institute at the Technical University of Crete (TUC) is an independent research institute established by the Greek Ministry of Education in 1995. Its mission is to spearhead basic and applied research in telecommunications and allied areas, contribute to graduate education, service, and outreach activities, and promote technological development at the regional and national level. TSI is affiliated with the Department of Electronic and Computer Engineering (ECE) at TUC. It contributes to the Department's graduate program and in turn draws senior researchers and graduate students. Owing in part to a highly successful targeted recruiting effort in concert with the Department of ECE, TSI has developed a pool of senior researchers with world-class credentials. Most have earned their Ph.D. and worked as faculty or members of technical staff at major Universities and research labs in the U.S. and Europe.

TSI's research activities span telecommunications, networking, signal processing, data mining, and telecommunication system hardware. The group is proud of its academic accomplishments: credits include 7 IEEE society-level best journal paper awards, and several prestigious IEEE-level appointments. Since 2003, TSI has coordinated or participated in 11 FP6/FP7 projects (SAVE, U-BROAD, MUSCLE, HI-WIRE, BIOPATTERN, OPTAG, COOPCOM, AWISSENET, OSMOSIS, SMART, COMON), 6 projects from the Greek Secretariat for Research and Technology, 3 regional development programs, and several smaller-scale projects funded by industry.

Athanasios Liavas, received his Diploma and PhD from the University of Patras, in 1989 and 1993, respectively. From 1993 to 1995 he served in the Greek Army. He spent the years 1996 to 1998 at the Institut National des Telecommunications, Evry, France, as a Marie Curie postdoctoral Fellow. From 1999 to 2001 he was visiting Assistant Professor at the Department of Informatics, University of Ioannina. In 2001, he became an Assistant Professor at the Department of Mathematics, University of the Aegean. In 2004, he joined the Department of Electronic and Computer Engineering, Technical University of Crete, as Associate Professor. In September 2009, he became Professor and Department Chair. Dr. Liavas served as an Associate Editor for the IEEE Transactions on Signal Processing from 2005 to 2009. He is an elected member of the IEEE Signal Processing for Communications and Networking Technical Committee (first election 2006, re-elected 2009). Prof. Liavas has been Project Coordinator and PI for TSI for the FET-Open project COOPCOM (Cooperative and Opportunistic Communications for Wireless Networks). His research interests are in digital communications, information theory and coding, and signal processing.

Michail G. Lagoudakis is an assistant professor with the Department of Electronic and Computer Engineering (ECE) at the Technical University of Crete (TUC), Greece since 2005. Prior to this appointment, he held a post-doctoral fellow position at the Georgia Institute of Technology, USA, from 2003 to 2005. He received his Ph.D. degree in Computer Science with distinction from Duke University, USA, in 2003. He also holds a M.Sc. degree in Computer Science from the University of Louisiana, Lafayette, USA (1998) and a Diploma degree in Computer Engineering and Informatics from the University of Patras, Greece (1995). His research interests are mainly in Machine Learning and Robotics with extensive research experience and expertise in the area of Decision Making under Uncertainty and Reinforcement Learning. His research experience in Robotics includes path planning, motion control, skill learning, and multi-robot coordination. Lagoudakis has published 6 refereed journal papers and 34 refereed conference papers which have received more than 600 citations from other researchers so far. Soon after his arrival at TUC, he founded "Kouretes", the first Hellenic RoboCup team, which participates in RoboCup competitions since 2006 and has already won international distinctions. Lagoudakis has received a Marie Curie International Reintegration Grant (2006) from the European Commission and two Basic Research Grants (2007 and 2009) from TUC to fund his research. He has served as a member on 26 program committees of various international conferences and as a reviewer on 22 scientific journals and 25 international conferences. Lagoudakis is a member of the RoboCup Standard Platform League Executive Committee since 2009 and was co-chair of the 13th International RoboCup Symposium held in

Graz, Austria in 2009.

B2.2.6. IMPERIAL – IMPERIAL COLLEGE LONDON

www.imperial.ac.uk

Imperial College London is among the top 10 universities in the world. Its Electrical and Electronic Engineering Department has about 50 academics and about 1000 students, undergraduate and postgraduate. It is organized in 5 research Groups, doing research on power and control, intelligent systems, signal and image processing, communications and nanotechnology. The Communications and Signal Processing Group consists of 8 academics and about 80 PhD students and postdoctoral students. It has been very active in attracting funding from European, National and Private sources, with a current portfolio of grants of about 5 million pounds. The Group has had recently a large number of projects funded by the Defense Technology Centers, and concerned with target detection and tracking through the fusion of information coming from a variety of sources, including radar, optical and infrared sensors. The Group has state of the art equipment for sound research, photometric stereo and the Smart Environment Lab which has sensors like seismic, pressure, sound, optical, etc, as well as equipment for cognitive studies like an eye-tracker, flock of birds camera systems and EEG.

Professor Petrou studied Physics at the Aristotle University of Thessaloniki, Greece, Applied Mathematics in Cambridge and she did her PhD in the Institute of Astronomy in Cambridge, UK. She obtained her DSc also from Cambridge in 2009.

She has published more than 350 scientific papers, on Astronomy, Remote Sensing, Computer Vision, Machine Learning, Color analysis, Industrial Inspection, and Medical Signal and Image Processing. She has co-authored two books "Image Processing: the fundamentals", first edition 1999, second edition 2010, and "Image Processing: dealing with texture", 2006, both published by John Wiley. She has also co-edited the book "Next generation artificial vision systems: reverse engineering the human visual system". She has supervised to successful completion 41 PhD theses. She is a Fellow of the Royal Academy of Engineering, Fellow of the City and Guilds Institute, Fellow of IET, Fellow of IAPR, Fellow of the Institute of Physics, Senior member of IEEE and a Distinguished Fellow of the British Machine Vision Association.

Professor Petrou was the coordinator of the Basic Technology grant on Reverse Engineering the human Vision system, that was funded by the UK Research Councils with 2.7 million pounds for a period of 4 years, and a translation grant with the same name currently funded with 1.1 million pounds.

She has worked on underwater inspection and on land buried pipeline mapping with British Gas. More recently she has been working on the application of photometric stereo to 3D surface reconstruction, with particular emphasis on 3D face reconstruction and recognition, with two grants awarded by EPSRC. Also, she worked on cognitive vision through the EU funded eTRIMS project, which finished in September 2009, concerned with the problem of learning to recognise components in the built environment.

Dr. Tae-Kyun Kim is a Lecturer in the computer vision and learning at the Imperial College London, UK, since 2010. He obtained his PhD from Univ. of Cambridge in 2007 and was subsequently a junior research fellow of Sidney Sussex College in Cambridge during 2007-2010. His research interests span various topics of computer vision, learning and perception, including: object recognition, tracking, face recognition and surveillance, action/gesture recognition and sematic image segmentation and reconstruction. He has published as the first author over 40 top-tier highly cited journal and conference papers, including TPAMI, IJCV journals and CVPR/ICCV/ECCV/NIPS conferences. He has been regularly invited to give a tutorial at major conferences (e.g. ICCV, MVA) and summer schools (ICVSS), and serve as a TPC. He has also co-authored 6 MPEG7 standard documents and over 17 international patents. His authored algorithm is an international standard of MPEG-7 ISO/IEC for face image retrieval. He is presently with 8 PhD students and 2 postdocs, and PI of the EPSRC first grant (EP/J012106/1) and two of industrial grants with Samsung and Omron.

Andrew Davison received the B.A. degree in physics and the D.Phil. degree in computer vision from the University of Oxford in 1994 and 1998, respectively. He undertook his doctoral with Prof. David Murray at Oxford's Robotics Research Group, where he developed one of the first robot simultaneous localisation and mapping

(SLAM) systems using vision. He was then a European Union (EU) Science and Technology Fellow at the National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Japan, for two years, where he continued to work on visual robot navigation. In 2000 he returned to the University of Oxford as a Postdoctoral Researcher and was awarded a five-year Engineering and Physical Sciences Research Council (EPSRC) Advanced Research Fellowship in 2002. During this time he developed the well known MonoSLAM algorithm for real-time SLAM with a single camera. He joined Imperial College London in 2005, and in 2012 was promoted to the position of Professor with the Department of Computing and leads the Robot Vision research group. His current research interests focus on advancing the basic technology of real-time localization and mapping using vision while collaborating with industry to apply these techniques in robotics and related areas. Since 2008 he has held a European Research Council (ERC) Starting Grant to support this research.
Akis Tsiotsios received his MEng degree in Electrical and Computer Engineering in 2010, from Aristotle University of Thessaloniki, Greece. He completed his Master's thesis in collaboration with Informatics and Telematics Institute of Thessaloniki and he was a visiting student in the Department of Electronics, University of Barcelona in 2008. He is currently working towards a PhD degree in the Department of Electrical and Electronic Engineering in Imperial College London. His research interests include computer vision, underwater vision and photometric stereo.

B2.2.7. MST– OCEANSCAN - MARINE SYSTEMS & TECHNOLOGY, LDA
www.oceanscan-mst.com
OceanScan-MST is a spinoff from Porto University's Underwater Systems and Technology Laboratory. The working team designs, develops and sells systems for oceanographic surveys, environmental monitoring and security applications. The company has an innovative approach to develop tools, vehicles, systems and technologies for the cost-effective access to the Ocean. Its approach is based on three key concepts: (1) open systems; (2) continuous technological integration; (3) co-developed solutions and operational experience with the users. OceanScan-MST offers an important contribution to the segment of lightweight, low logistics and low cost AUVs. As the main product, the company produces the Light Autonomous Underwater Vehicle (LAUV), which is a European low-cost AUV for oceanographic and environmental surveys designed and built at Porto University. The LAUV system was awarded the Portuguese BES2006 innovation prize.
Luis Madureira received his diploma degree in 2000 from the Electrical and Computer Engineering department of the Engineering Faculty of the Porto University, Portugal. In 2005 he completed his master degree in Electrical and Computer Engineering, were he developed work in acoustic navigation systems for multiple underwater vehicles. From 2000 to 2008 he was part of the Underwater Systems and Technology Laboratory of the Porto University research group, were he developed functions related with development, deployment and evaluation of underwater vehicles and systems. Since 2008 is part of OceanScan-MST as promoter and managing partner.
Alexandre Sousa received his diploma degree from the Electrical and Computer Engineering department of the Engineering Faculty of the Porto University, Portugal, in 2001. In 2005 he completed his Post-Graduation in Industrial Informatics. From 2001 to 2008 he was part of the Underwater Systems and Technology Laboratory of the Porto University research group, were he was involved in several R & D projects related with underwater vehicles and systems. Since 2008 is part of OceanScan-MST as promoter and managing partner.

B2.2.8. APDL – Administração dos Portos do Douro e Leixões, SA

www.apdl.pt

The **Port of Leixões** comprises the largest seaport infrastructure in the **North of Portugal** and one of the most important in the country. With 5 km of quays, 55ha of embankments and 120 ha of wet area, Leixões has excellent road, rail and maritime accesses and is equipped with advanced information systems for vessel's traffic control and management. Representing **25% of the Portuguese foreign trade** and handling 15 million tons of commodities a year, the Port of Leixões is one of the most competitive and versatile multi-purpose ports in the country. Around 3.000 vessels a year come through Leixões, carrying all sorts of goods: textiles, granites, wines, timber, vehicles, cereals, containers, scrap metal, iron and steel, alcohol, schnapps, sugar, oil, molasses, petroleum products, and even passengers from Cruise Liners. **Concessionaires**, who own the most up to date equipment, predominantly handle the traffic of commodities in Leixões. The Port Authority provides Pilotage, Towage and Mooring services and is equipped with the most up-dated means and equipment. Benefiting from a strategic location with a hinterland rich in industry and commerce, the **Port of Leixões** has a privileged position in the context of the European port system. It operates 365 days a year with high productivity levels and with reduced vessels turnaround time at the quays. The bar entrance is always open to navigation, without sea tide restrictions

The Port Authority of Douro and Leixões (APDL - Administração dos Portos do Douro e Leixões, S. A.) is a state-owned company, aimed at the administration of the Ports of Douro and Leixões, its economic operations, conservation and development. The General Assembly, the Board of Directors and one Auditor make part of the public limited company.

Port Authority Jurisdiction Area

The area under jurisdiction of the Port Authority of Douro and Leixões comprises the coastal strip of maritime public domain, from the point of Rua da Bélgica, at Praia de Lavadores, to the parallel of Boa Nova lighthouse, North of the Port of Leixões, besides the following areas:

a) The area of the Port of Douro which comprises the whole estuary of the river Douro, from 200 meters upstream the Luiz I bridge to the river mouth, including its margins and all the berths, quays, docks and available areas existing or to be built.

b) The area of the Port of Leixões which comprises the breakwaters, the sea area they limit and the docks existing or to be built, the course of the river Leça up to the old Guifões windmills bridge and the land area limited by the respective public domain.

Emilio Fernando Brogueira Dias is a Board Member of APDL, with the management of the:

- Port Operations and Port Safety and Security Direction
- Port Works and Equipment Direction

Participation, coordination and direction of Professional Associations like the Chamber of Engineers, the Portuguese Association of Water Resources, Institute of Hydraulics and Water Resources, International Association of Navigation Congresses, Risk Centre of the Oporto University.

Miguel Nuno Gomes Quadros Lázaro da Silva is the responsible for the Hydrographic surveying area, integrated in the Works Division of the Port Works and Equipment Direction of APDL.

Rui Manuel Carreira Henriques da Cunha is the Director of Port Operations and Port Safety and Security Conditions, with responsibility in the areas of Safety and Environment, Planning and Coordination of Navigation, Vessel Traffic System, Maritime Operations, Pilotage Service and Control of Port Activity.

João Pedro Moura Castro Neves is the division Chief of APDL Works, responsible for the execution projects development and for the implementation and supervision of major works undertaken by APDL in the port of Leixões.

B2.2.9. CNRS - Centre National de la Recherche Scientifique (CNRS)

http://www.georgiatech-metz.fr

http://dream.georgiatech-metz.fr

As the result of a strategic alliance between the Georgia Institute of Technology (GIT) and the French Centre National de la Recherche Scientifique (CNRS), a joint GIT/CNRS research laboratory, the GT-CNRS UMI 2958, was established at the Georgia Tech Lorraine campus in Metz, France, in March of 2006. So far, the laboratory has been conducting a unique transatlantic collaborative program of research in secure networks and smart materials. Research faculty and graduate students from Georgia Tech, French universities, and other CNRS laboratories work on joint research projects sponsored by industry and by local and national governments. The founding associate partners in this unique laboratory are the University of Metz, the University of Franche-Comté, the Ecole Nationale Supérieure d'Arts et Métiers (ENSAM), and L'École Supérieure d'Électricité (Supélec). Initial research programs focus on optoelectronic techniques for signal encryption and secure transmission for optical and wireless systems, nonlinear optics, new materials and nanostructures for photonics and electronics, multifunctional materials, the ultrasonic characterization of materials, and the development of new ultrasonic sensors

Prof. C. Pradalier has been appointed at the UMI in September 2012 with the objective to extend the activity of the UMI towards robotics, leveraging on one side the strong robotic research inside CNRS and on the other side the collaboration potential with the Robotics and Intelligent Machines (RIM) laboratory at GeorgiaTech Lorraine. He brought over his experience on autonomous boat and underwater system gathered at the Autonomous Systems Lab at ETH Zürich, Switzerland and at the Autonomous Systems Lab at CSIRO, Australia. At ETH Zürich, Prof. Pradalier led the development of two autonomous boats: a sailing boat designed to participate to the micro-transat competition and an electric boat used in the Limnobotics project to monitor the water quality in fresh water lakes, and in particular the lake of Zürich. More details about the project can be found on www.limnobotics.ch. He also supervised the development of an autonomous sailing boat using foils to stabilise its attitude over the water surface, an autonomous robotic fish and the development of an autonomous robotic sea-turtle. At CSIRO, Prof. Pradalier was involved in the development of the software systems for the Starbug AUV, and in particular the middleware for data exchange on-board and the management of the set of behaviors constituting a complete mission. With the UMI, he is contributing his experience of field robotics and real-world deployment, as well as his experience in developing control software for autonomous surface crafts, with the aim to develop tools for autonomous environment monitoring over long durations.

Within Noptilus, the main task of the UMI will be the development of the control software sensory-motor trajectory following and the integration of this control mode with the more traditional control approaches developed by the other partners.

Prof. Cédric Pradalier started as Associate Professor at the CNRS UMI-2958 in September 2012, with the objective to create the DREAM lab, a robotic laboratory focused on applied mobile robotics and in particular long-term deployment and environment monitoring. From November 2007 to August 2012, Dr. C. Pradalier was deputy director of the Autonomous Systems Lab at ETH Zürich, in collaboration with Prof. Roland Siegwart. He has been the technical coordinator of the V-Charge project (IP, 2010-2014) and has also been involved in the development of innovative robotic platforms such as autonomous boats for environment monitoring or prototype space rovers funded by the European Space Agency. He is a founding member of the ETH start-up Skybotix, within which he was responsible for software development and integration. From 2004 to 2007, Dr. C. Pradalier was a research scientist at CSIRO, Australia. He was then involved in the development of software for autonomous large industrial robots and an autonomous underwater vehicle for the monitoring of the Great Barrier Reef, Australia. He received his PhD in 2004 from the National Polytechnic Institute of Grenoble (INPG) on the topic of autonomous navigation of a small urban mobility system and he is Ingénieur from the National Engineering School for Computer Science and Applied Maths in Grenoble (ENSIMAG).

Prof. Henrik Christensen is a distinguished professor of computing. He is the KUKA Chair of Robotics at Georgia Institute of Technology and the Director of Robotics and Intelligent Machines. Dr. Christensen has been an associate member of Georgia Tech Lorraine since 2006. He does research on systems integration, applied estimation and computer vision. Dr. Christensen earned his first degree in mechanical engineering. He worked in industry with MAG B&W before returning to academia. He was awarded M.Sc. and Ph.D. EE degrees from Aalborg University. Dr. Christensen's research has been commercialized by a rich variety of companies such as KUKA, ABB, Electrolux, Volvo, Yujin Robotics, Boeing Corporation, and iRobot. He has published more than 250 contributions across the areas of computer vision, artificial intelligence and robotics. He serves on the editorial board of the most prestigious journal in robotics such as International Journal of Robotics Research, Autonomous Robots, and Robotics and Automation. He is the co-editor in chief for Trends and Foundations in Robotics. He has lead a large number of EU projects and was the founder and coordinator of the European Robotics Research Network - EURON (1999-2007).

B2.3 Consortium as a whole

B2.3.1 CONSORTIUM

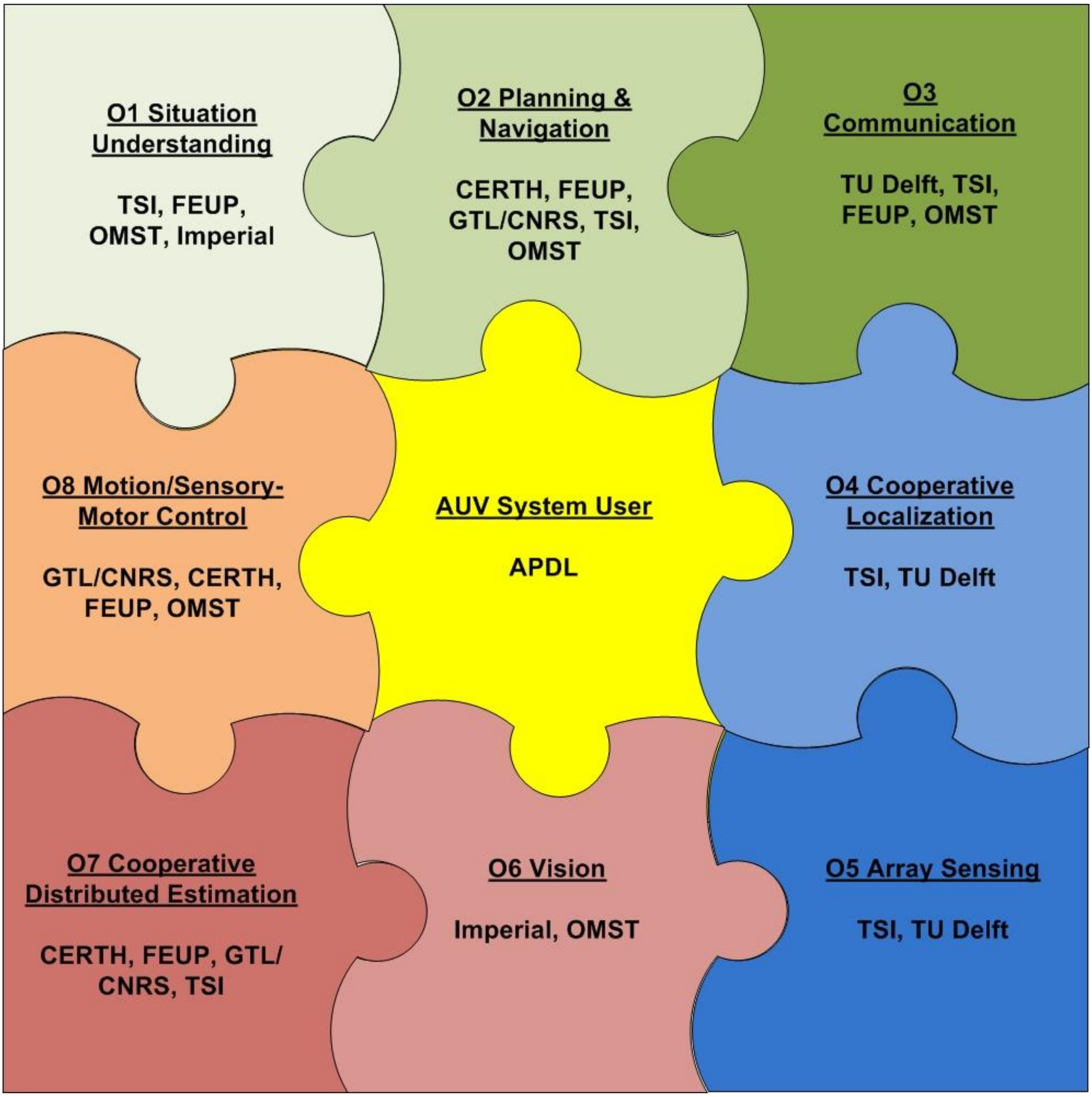


Figure 5. Puzzle of consortium and competences

The goal of the proposed project is to develop novel approaches and technologies in underwater communications, localization and sensing, distributed estimation and motion/sensory-motor control of underwater vehicles, automated situation understanding and autonomous motion design and integrate these technologies to a fully autonomous multi-AUV system. In order to successfully conduct this endeavor, we collected leading research groups, an AUV-designer/provider and a large-scale industrial partner (User) to a well balanced project team.

All NOPTILUS research partners belong to the technological leaders in their corresponding domains. Over the last years, they have continuously developed state-of-the-art techniques and systems in various areas including AUV design, navigation, perception, cognitive-based robotics, mapping, control and estimation for large-scale systems, multi-robot control, sensor networks, computer vision and telecommunication technology. Between the individual partners there are also overlapping interests and competences which guarantee that the interfaces are well understood. At the same time this also greatly facilitates the collaboration of the individual partners. The integration of these partners in the NOPTILUS consortium therefore will lead to a substantial synergy effect that will provide innovative solutions to the problem of autonomous multi-AUV systems. It will generate new concepts and technologies and result in the first demonstration of fully autonomous multi-AUV system. On the other hand, the 2 industrial partners of NOPTILUS involve one of the frontiers worldwide in the field of AUV design and deployment (the SME MST), and a user with a rich variety of large-scale underwater surveillance and monitoring needs.

The set of skills of the partners are appropriate for carrying out the work proposed either from the research, academic, or industrial side. In our view these organizations are ideally suited to achieve the goals of the project. They are a perfect mix of academia, industrial and operator partners, and of different areas of expertise.

The financial effort of each partner within the project, especially of the industrial partners and operators, is appropriate with respect to their annual turnover and research capabilities. All partners have the personnel and financial resources to carry out the work they are responsible for within the project.

CERTH, the project coordinator carries a lot of experience in coordinating projects of the scale and complexity of NOPTILUS. The Information and Telematics Institute of CERTH (where the particular coordinating team of NOPTILUS belongs) has been coordinating many large-scale EU-funded projects, now and in the past. The particular team that will coordinate NOPTILUS has a rich experience and involvement in EC-funded projects; it has participated in more than 20 EC-funded projects (STREPs and IPs) over the last years, by being the project coordinator in 3 of them (among them the currently running ICT FP7 projects PEBBLE on large-scale sensor and control systems for Energy Positive Buildings and AGILE on large-scale self-tuneable and re-configurable control system design) and the technical coordinator in 4 of them. The team is a world leading research team in intelligent and learning control and decision-making. The developed research results by the team have found their way to industrial applications of large-scale decision-making and control systems with hundreds of real-life implementations world-wide. This expertise naturally complements with the others towards the development of estimation and learning-based decision-making designs for autonomous multi-AUV systems. CERTH will take the lead in WP4 where it will strongly interact with FEUP, ETH Zurich and TSI for the development of efficient cooperative and distributed estimation techniques; also it will provide the motion control design (WP5) and, finally, it will lead WP7 (in close cooperation with FEUP and TSI) in order to enhance and further develop its recently-developed intelligent multi-robot approach into a generic fully-automated tool for multi-AUV planning, assignment and navigation.

FEUP is the core NOPTILUS research partner in underwater robotic systems. One of the frontiers worldwide in the field of underwater robots, has been involved in many EU-funded projects (related to underwater robots and applications); most importantly, FEUP is one of the few academic institutions worldwide with a unique experience in real-life AUV applications: these include some world firsts, such as the underwater rendezvous between the *Aries* and *Isurus* AUVs (in cooperation with UC Berkeley); design and delivery of AUVs for the Portuguese Navy; the Extension of the Continental Shelf; and the *Raia* project on ocean observation. FEUP will co-lead (with MST) all the system specification, integration and demonstration activities of NOPTILUS and have a significant role in WP4 and WP7. FEUP will be also leading the dissemination, training and exploitation activities of NOPTLUS (WP9).

ETH Zurich has a long history in developing robotic systems that can reliably fulfill their tasks in dynamic and potentially unstructured environments. The particular ETH Zurich lab that will carry the work within NOPTILUS (ETH Zurich – ASL) is one of the largest and most renowned robotics labs in Europe with involvement in plenty of different projects covering all areas of robots and their applications. The role of ETH Zurich within NOPTILUS will be mainly in providing the NOPTILUS sensory-motor control (WP5) design as well as to contribute in Cooperative Distributed Estimation (WP4). After the first reporting period (months 1-18), Prof. C. Pradalier (the PI on behalf of ETH Zurich) assumed a new position with the **CNRS** and, as a result, all the activities that ETH Zurich was responsible for Months 19-48 of the project will be undertaken by CNRS.

TU Delft will have a major role in WP3, by leading the work on the design and implementation of the sonar-based collaborative telecommunication system of NOPTILUS as well as in assisting in the design of localization and sensing systems of NOPTILUS. The group of TU Delft – under the leadership of Professor Dr. Geert Leus – has a deep involvement in wireless and underwater communications. They have been developing communication algorithms and systems for a variety of acoustic modems/underwater communication systems for AUVs.

TSI comprises 2 different groups:

(a) The group of Professor A. Liavas, will lead the work of WP3 on the design of localization and sensing systems of NOPTILUS. An international leader in MIMO-based sensor networks, which will serve the basis for the developments of his team within NOPTILUS.

(b) The group of Professor M. Lagoudakis that will lead the work of WP6 (Situation Understanding) and have a central role in WP4 on the development of cooperative distributed estimation algorithms. Professor Lagoudakis research interests focus on cognitive- and learning-based robotics. He founded "Kouretes", which participates in RoboCup competitions since 2006 and has already won international distinctions.

Imperial will lead the work on NOPTILUS vision systems and the fusing of their signals with the sonar-based ones. The particular team of Imperial that works within NOPTILUS is one of the leaders worldwide in vision systems and image recognition.

MST is a dynamic SME – and one of the few of its kind worldwide – focusing on designing, developing and selling lightweight, low logistics and low cost AUVs for oceanographic surveys, environmental monitoring and security applications. MST will co-lead (with FEUP) all the system specification, integration and demonstration activities of NOPTILUS. MST will also have a significant role in all other technical WPs, mostly in order to make sure that the developed methodologies and algorithms satisfy the requirements and needs of multi-AUV systems.

Finally, **APDL**, is the NOPTILUS user which provides its premises to serve as the NOPTILUS Test Case. It has to be emphasized that APDL is involved almost daily in a large variety of underwater surveillance, monitoring, etc operations that rely – in their majority – on divers (and only a small portion of them employs human-operated ROVs). Apart from being the NOPTILUS user, APDL will provide its rich collection of underwater data to be used for the learning approach of WP6. Finally, we have to emphasize the will of APDL to adopt the NOPTILUS system on a permanent basis.

Apart from the above mentioned contributions of the individual partners, all partners will be deeply involved in the dissemination and exploitation activities of the project.

THIRD PARTIES

Georgia Tech Lorraine (GTL) is added to the consortium as a third party to beneficiary Centre National de la Recherche Scientifique (CNRS).

SUB-CONTRACTING

No subcontracting (except for audit certificates)

OTHER COUNTRIES

No other countries.

B2.4 Resources to be committed

REQUESTED EC CONTRIBUTION

Human power

The proposed research work will mainly be conducted by the following persons financed through the project:

			CERTH	FEUP	ETHZ	TU Delft	TSI	Imperial	MST	APDL	CNRS	**TOTAL**
		Senior Researchers	12.0	22.0	-------------	5.0	26.0	4.0	-------------	-------------	3.0	**72.0**
		Junior Reseachers/Post Docs	32.0	24.0	7.2	0.0	0.0	53.0	-------------	-------------	-------------	**116.2**
		PhD Students	36.0	24.0	7.2	28.0	50.0	0.0	-------------	-------------	20.0	**165.2**
		Senior Engineers	-------------	-------------	-------------	-------------	-------------	-------------	60.0	10.0	-------------	**70.0**
		Engineers/Software Developers	12.7	15.0	-------------	-------------	-------------	0.0	16.0	-------------	-------------	**43.7**
		Technicians	0.0	15.0	-------------	-------------	-------------	0.0	28.0	17.0	-------------	**60.0**
		Adminstrative Staff	9.2	14.0	-------------	0.0	11.0	0.0	18.0	13.0	4.0	**69.2**
TOTAL			101.9	114.0	14.4	33.0	87.0	57.0	122.0	40.0	27.0	**596.3**

An overview on the distribution of the person-months across the different work packages can be found in Section B1.3.7. These core persons will be supported by complementary resources from the involved partners as listed in the next Section.

Finances

As seen in the table below showing the NOPTILUS budget overview, the majority of the financial resources are used to cover the personnel costs. Other direct costs include equipments, consumables, travel and the audits (subcontracted: 1500 Euros are foreseen for all partners whose budget exceeds the amount 375,000 Euros, except for partner Imperial who has foreseen 2500 Euros).

The equipment and consumable costs are listed below:

Equipment

Equipment for AUVs, ASVs, Control Center, etc		
Type of Equipment	**No of Units**	**Total Cost**
3 Evologics modems	3	22375
DVLs	3	45000
PC-104 stacks	10	10000
IMUs	6	18000
Motors	6	4000
thrusters seaeye	2	10000
trolling motors	2	10000
pelli cases	6	3000
laptops (control station)	4	6000
Wifi modules	various parts	2000
GSM modules	various parts	2000
Side-scan sonars	various parts	20000

Batteries	various parts	10000
Misc.	various parts	5000
Equipment for Vision Systems		
AUVs vision systems: 1 fast underwater camera (500 frames per second) along with 5-6 strong lights installed on the vehicle and underwater cage.	4	40000
Vision system for performing experiments at Imperial (1 fast underwater camera along with 2-3 lights)	1	8000
Expenses (consumables) for running the tests/demos		
Preliminary Tests and Integration Week 1 (1 zodiac for 10 days; cost of zodiac is 250Euros/day)		2500
Integration Week 2 (2 zodiacs and 1 big boat for 10 days; cost of zodiac is 250Euros/day and the cost for the big boat is 500Euros/day)		10000
Integration Week 3 (2 zodiacs and 1 big boat for 10 days; cost of zodiac is 250Euros/day and the cost for the big boat is 500Euros/day)		10000
Integration Week 3 (2 zodiacs and 1 big boat for 24 days; cost of zodiac is 250Euros/day and the cost for the big boat is 500Euros/day)		24000
gasoline for AUVs generators as well as other consumables that will be needed for equipping the divers, filming the underwater tests		1500
PCs and consumables for CERTH, ETH Zurich, Imperial		
2 laptops for running the simulation tests and for receiving/exchanging data with the control centre and the AUVs		3000 per partner
Software Licenses for underwater robotic simulation		7000 per partner
Consumables for TSI and TUDelft		2000 per partner
TOTAL EQUIPMENT		**297375**

The costs under the category "**Equipment for AUVs, ASVs, Control Center, etc**" cover the expenses of equipping (upgrading) 6 AUVs, the ASV, the fixed components and the control centre with all necessary components for running NOPTILUS demonstrations. The budget of the partners FEUP, MST and APDL includes these equipment costs by splitting them depending on which partner will be responsible for installing and running the respective component.

Please note that the AUVs and ASVs as well as the other equipment described in Section B1.1.4 is already available at the Test Site and thus there will be no cost for such equipment charged to the project.

There will be total 5 underwater cameras acquired. One of those will be acquired by the Imperial Colleague for performing underwater tests at their premises, while 4 cameras will be mounted on the AUVs (along with the strong lights and the underwater cage). The cost of the camera for performing the tests at the Imperial is estimated at 8000 Euros, while each of the cameras to be mounted on the AUVs along with the strong lights and the cage have a total estimated cost of 10000 Euros.

A total of 48000 Euros is also foreseen for expenses (consumables) that will be needed during the tests, integration weeks and demonstrations. These expenses – included in the budgets of the partners FEUP, MST and APDL – have been calculated based on experience on running tests and demos in the past, and cover the costs

- for running the boats to be used during the experiments; The cost for running one zodiac is around 250 Euros/day and the cost for a bigger boat – to be used in the experiments outside the port – is around 500 Euros/day. One zodiac will be needed for the tests inside the port and 2 zodiacs and one bigger boat will be used in the tests outside the port.
- gasoline for AUVs generators as well as other consumables that will be needed for equipping the divers, filming the underwater tests, etc.

Finally, the amount of 10000 Euros is foreseen for all partners (except for FEUP, MST and APDL consumables are already included under "**Expenses (consumables) for running the tests/demos**") for PCs, consumables, etc. This includes budget for

- purchasing licenses for dedicated software necessary to run simulations of underwater operations;
- 2 laptops for running the simulation tests and for receiving/exchanging data with the control centre and the AUVs.

2-3 licenses per partner for software that provides all necessary tools for developing a complete simulation environment for the 3 NOPTILUS basic test case scenarios will be purchased. Software tools such as MSRDS or MarineSim will be considered towards such a purpose. It has to be emphasized that the simulation environment to be developed should model the underwater operations and phenomena in very detail so that all of NOPTILUS' modules and operations will be tested in an integrated manner. In other words, the simulation environment to be developed will model not only the high/medium-level operations of NOPTILUS (e.g. trajectories of AUVs, control logic for AUVs, sensing and mapping modules, etc) but also the low-level operations and phenomena such as the acoustic communication systems, effect of currents and turbulences, effect of underwater phenomena to AUV dynamics and to sonar and vision systems, etc. For this reason, a coherent approach will be adopted to the purchasing of simulation software and the development of the simulation environment, by ensuring that the simulation software to be purchased meets all requirements for modeling in detail all the underwater operations and phenomena as well as that the particular simulation modules to be developed by individual partners (e.g. module for simulation the underwater communication system) are compatible and easily connected/integrated with the rest of the modules. Additionally – and having in mind that one of the NOPTILUS ambitions is that the simulation environment to be developed within NOPTILUS will serve as a benchmark to the underwater robotics community – all possible efforts will be made so that an open-source approach is adopted to the development of the simulation environment, rendering it easily accessible to researchers and developers for testing their own developments. Finally, coordination between NOPTILUS and the other underwater robotics FP7 project will take place in order to make all possible efforts so that the simulation software to be developed within NOPTILUS is compatible with the ones developed in the other projects and that all projects share simulation software modules and interfaces in an attempt to avoid the situation where different projects devote effort for developing simulation modules/interfaces that serve exactly the same purpose.

Travel Expenses

Trip Purpose	CERTH	FEUP	ETHZ	TU Delft	TSI	Imperial	MST	APDL	CNRS	TOTAL
1st Project Review - Porto	1500	**1000**	0	1500	1500	1500	**1000**	**1000**	0	9000
2nd Project Review - Porto	1500	**1000**	0	1500	1500	1500	**1000**	**1000**	1500	9000
3rd Project Review - Porto	1500	**1000**	0	1500	1500	1500	**1000**	**1000**	1500	9000
4th Project Review - Porto	1500	**1000**	0	1500	1500	1500	**1000**	**1000**	1500	9000
Total MGT travel	6000	4000	0	6000	6000	6000	4000	4000	4500	36000
1st Consortium meeting	1500	**2000**	873.18	1500	1500	1500	**0**	**1000**	0	9873.18
2nd Consortium meeting	**1000**	1500	519.22	1500	1000	1500	1500	1500	0	10019.22
3rd Consortium meeting	1500	1500	**0**	1500	1500	1500	1500	1500	**1000**	10500
4th Consortium meeting	1500	1500	0	**1000**	1500	1500	1500	1500	1500	10000
5th Consortium meeting	1000	1500	0	1500	**1000**	1500	1500	1500	1500	9500
6th Consortium meeting	1500	1500	0	1500	1500	1500	1500	1500	1500	10500
7th Consortium meeting	**1000**	1500	0	1500	1000	1500	1500	1500	1500	9500
8th Consortium meeting	1500	**2000**	0	1500	1500	1500	**0**	**1000**	1500	9000
4 Concentration Meetings	4800	4800	0	0	0	0	0	0	0	9600
Integration Weeks/Demos/RTD Conference Travel	34000	**20000**	438.61	7500	34700	24500	**0**	**7500**	34800	128638.6
TOTAL RTD travel	49300	37800	1831.01	19000	45200	36500	9000	18500	43300	217131
Schools & Training	2000	2000	0	2000	2000	2000	2000	2000	2000	14000
Conference attendance	8000	8000	0	4000	8000	8000	8000	0	8000	44000
TOTAL Other travel	10000	10000	0	6000	10000	10000	10000	2000	10000	58000

The bold figures in the above Table indicate the host or co-host of the meeting. 8 total consortium meetings are foreseen (two per year). For most trips each partner will be represented by one person only, but in certain cases the budget allows for two persons to attend consortium meetings. Please also note that the sequence of hosting the consortium meetings may be changed during project's life-time. One trip per year is foreseen for annual review meetings in Porto (Test Case) and one trip per year is foreseen for concentration meetings in the central Europe. 2 NOPTILUS people will attend the concentration meetings: one representative from the project coordinator and one representative from FEUP.

The travel budget also includes the travel expenses (along with expenses for hosting) of the preliminary underwater tests, the 3 project integration weeks and the demonstrations as well as conference attendance and the expenses of the project's summer schools.

NOPTILUS Budget

		CERTH	FEUP	ETHZ	TU Delft	TSI	Imperial	MST	APDL	CNRS	TOTAL
RTD	Personnel Costs	460104	364000	89808	133252	320000	274552	264432	228550	119598	2254297
	Travel	49300	37800	1831	19000	45200	36500	9000	18500	43300	260431
	Equipment& consumables	10000	122375	0	2000	2000	18000	47000	86000	10000	297375
	Indirect Costs	368083	314505	54984	153387	220320	197431	192259	66610	103739	1671318
	Total Costs	887487	838680	146623	307639	587520	526483	512691	399660	276637	4483420
	Requested EC Contribution	665616	629010	109967	230729	440640	394863	384518	199830	207478	3262651
DEM	Personnel Costs	0	0	0	0	0	0	0	0	0	0
	Travel	0	0	0	0	0	0	0	0	0	0
	Equipment& consumables	0	0	0	0	0	0	0	0	0	0
	Indirect Costs	0	0	0	0	0	0	0	0	0	0
	Total Costs	0	0	0	0	0	0	0	0	0	0
	Requested EC Contribution	0	0	0	0	0	0	0	0	0	0
MGT/OTH	Personnel Costs	18800	35000	0	23795	28000	15253	23610	32650	41859	218967
	Travel	16000	14000	0	12000	16000	16000	14000	6000	14500	108500
	Subcontracting (audit)	1500	1500	0	0	1500	2500	1500	0	0	8500
	Indirect Costs	15040	29400	0	27390	26400	18752	22566	7730	33816	181094
	Total Costs	51340	79900	0	63185	71900	52505	61676	46380	90175	517061
	Requested EC Contribution	51340	79900	0	63185	71900	52505	61676	46380	90175	517061
ALL	Personnel Costs	478904	399000	89808	157047	348000	289805	288042	261200	161457	2473264
	Travel	65300	51800	1831	31000	61200	52500	23000	24500	57800	368931
	Equipment & consumables	10000	122375	0	2000	2000	18000	47000	86000	10000	297375
	Subcontracting (audit)	1500	1500	0	0	1500	2500	1500	0	0	8500
	Indirect Costs	383123	343905	54984	180777	246720	216182	214825	74340	137554	1852411
	Total Costs	938827	918580	146623	370824	659420	578987	574367	446040	366812	5000481
	Requested EC Contribution	716956	708910	109967	293914	512540	447367	446194	246210	297652	3779711

COMPLEMENTARY RESOURCES BY PARTNER

Additionally to the key resources requested for this project, the partners of the consortium contribute with own resources and infrastructures to the success of this project. The main complementary contributions of the partners are:

- Through co-financing of PhD students for all academic partners.
- Permanent personnel costs covered by their regular salaries (mostly for administration and faculty personnel as well as for technicians of the two industrial partners).
- Equipment and software, purchased on partner's own expenses, which will be used within NOPTILUS.

Especially for the partners TUDelft, ETH Zurich, CNRS and Imperial most of the effort for their senior personnel will be contributed through the partners' own resources (part of the regular salaries of the senior personnel).

B3. IMPACT

B3.1 Strategic Impact

B3.1.1 DIRECT AND INDIRECT IMPACTS

Underwater exploration, mapping and situation-awareness operations present formidable difficulties and challenges at many levels. Current best practices involve the use of ROVs, deployed and operated by expert personnel. Human cognitive faculties are utilized in all instances of their operation: to maneuver, to identify and recognize areas of interest, to predict evolution in the case of timed events, to understand the situation and take actions as and when needed. There are numerous problems associated with ROVs operation: (a) in the case of wired *communication* each ROV has limited operational range, while in the case of wireless communication the aqueous environment is an unforgiving medium allowing communication only at very low data-transfer rates (typically a few Kbps); (b) *uncertainties* are ubiquitously present: underwater currents and turbulence affect movement, limited sensing and communication capabilities yield low-quality high-entropy information, multipath effects and Doppler shifts prevent reliable communication, localization is inaccurate due to the unavailability of GPS signals and high communication latency; and, (c) perhaps the biggest weakness of current systems is their reliance on *humans* – currently, the actual enablers for ROV operation - who are prone to errors and their “expertise” is by no means a guarantee of performance or quality of service. This last point is especially important; humans can easily be overwhelmed by the information overload, fatigue can act detrimentally to their performance, properly coordinating multi-ROV actions is hard, and continuous operation is almost impossible. This is especially important in operational situations when time and/or precision is of essence as, for example, in the case of a shipwreck that spills a hazardous chemical through holes in its hull. A rapid and effective response can separate a properly-contained chemical and successful resolution of an unlucky event, from an ecological disaster with dreadful consequences to the ecosystem. More to this, increased operational cost due to inefficiencies and errors should also not be underestimated. The preceding discussion illustrates the pressing need for the **design and implementation of complete underwater robotic systems** that “challenge the perceived” and extend on what’s possible by overcoming the limitations mentioned above.

Within NOPTILUS we take the view that an effective fully-autonomous multi-AUV[5] concept/system, endowed with sensory and cognitive capabilities, will be able to overcome these shortcomings, by replacing human-operated monitoring and navigation operations by a fully autonomous one – restricting human operators, to a more-manageable and realistic high-level supervisory role. The work to be undertaken in NOPTILUS follows a hierarchical approach – with high-, medium- and low-level objectives – aiming, at each level, on the (parallel) development of (nearly-) orthogonal modules, capable of *replacing* basic functions of human cognition and intervention. As such the **development and integration of cognitive abilities** is pervasive throughout the Project: at the lowest level there is communication (O3), localization (O4), sensing (O5) and vision (O6); at the medium level there is motion/sensory-motor control (O7), as well as mapping and process tracking (O8); and at the higher level there is situation-awareness and process understanding (O1), and

[5] The view that AUVs present a viable solution is shared among many researchers and investigation is already under way as part of ongoing research work and/or other European Projects – the concepts, development and integration to be performed as part of the NOPTILUS Project are, to the best of our knowledge, original and will complement and enhance these efforts.

planning, assignment, and navigation of AUVs (O2). To successfully attain these objectives significant advances beyond the state of the art are required as carefully laid out in the work plan: from the cognitive-based communications and sonars (low level), via GP-based estimation as well as perceptual sensory-motor and learning motion control (medium level), to learning- and cognitive-based situation understanding and motion strategies (high level). The modules – to be developed as part of NOPTILUS Project – can be viewed as a toolbox for underwater operation of multiple AUVs and can be independently utilized **in a wide range of application domains** providing **innovation capacity and leverage** far exceeding the confines of our Project.

Of paramount importance is the *integration* of all these modules and the demonstration of the NOPTILUS system in a realistic environment at the Port of Leixões. A scenario-driven approach, utilizing a team of six AUVs deployed with the task of performing pre-determined operations is planned. As part of this demonstration, a second important aspect of the NOPTILUS system – that of (near-) optimality – will be shown. Specifically, the autonomous multi-AUV planning, assignment and navigation (PAN) will be utilized to: maximize the acquired information and accuracy of the distributed estimation, recognition, and situation understanding of the operation(s) the NOPTILUS system has been deployed for; minimize the time and processing required for accomplishing the aforementioned operation(s); while, respecting the physical, communication, and computational system constraints and limitations. Evaluation of the performance of the overall NOPTILUS system will be performed with emphasis on its robustness, dependability, adaptability, and flexibility especially when it deals with **completely unknown underwater environments and situations "never taught before".** Moreover, its ability to provide **arbitrarily-close-to-the-optimal** performance, while operating continuously on a **24hours/7days-a-week** basis, will be assessed and demonstrated in realistic environments. Through verification of a comprehensive set of measurable objectives, the superiority of the NOPTILUS system will be validated and the resulting **significant increases of the quality of service of such systems and of their sustainability in terms of energy consumption, usability and serviceability** will be attested**.**

Better algorithms, tools, and cognition are key elements of the NOPTILUS Project and will provide a superior platform capable of achieving operational goals in a variety of sectors. As part of the project demonstration phase six exemplary operations will be undertaken: detailed benthic mapping with adjustable resolution; inspection of quays and other infra-structures; inspection of dredged and dump sites; rapid environmental assessment and environmental monitoring with unprecedented spatial and temporal resolution; inspection of ship hulls and other mobile structures; and support to disaster management. These operations will strengthen the belief that the NOPTILUS system can be effectively utilized in a large number of application areas, including, but not limited to: oceanographic **exploratory** missions for mapping the benthic environment, **professional services** like environmental-monitoring operations and rapid detection and containment of chemical spills, **assistance** in sea search and rescue operations, **inspection maintenance and repair** operations of ships, quays, and other underwater structures. In addition, reducing the need for expert personnel and improved operational efficiencies will *directly* lead to tangible financial benefits. The involvement of students in the Project and the organization by the NOPTILUS team of open-house fairs, summer schools, conference sessions and workshops will contribute to **education and training** of students, researchers and the society at large. Overall, direct and indirect actions, along with the successful implementation of the NOPTILUS Project will **improve the competitive position of the robotics industry in existing and emerging markets.**

Achieving the, rather ambitious, goals set in the NOPTILUS project, and before the aforementioned benefits can be reaped, significant advances beyond the state of the art are required in a number of areas. For this reason the NOPTILUS consortium comprises members that are world leaders and have demonstrated excellence in their respective areas. The fruitful interactions and cross-pollination of ideas that led to this research project proposal will continue more vigorously upon funding and commencement of the proposed work. An "extrovert approach" will be taken in communication of the findings and sharing of the developed tools to researchers, students, end-users, and operators. A comprehensive dissemination plan along with the diverse research group and effective communication strategies will lead to **integrated and consolidated scientific foundations for engineering cognitive systems under a variety of physical instantiations.**

B3.1.2 EUROPEAN ADDED VALUE

The mix of:

- combined expertise of the NOPTILUS partners and
- the need to convince stakeholders all over Europe, and beyond, that the NOPTILUS system is not just designed for some national niche market;

suggest that NOPTILUS could not be run as a national project with anything like the impact anticipated from this current proposal.

The fact that the user of NOPTILUS is clearly and demonstrably independent of the developers of the NOPTILUS system will lend much weight to the evaluation results. Finally, the fact that NOPTILUS partners come from various corners of Europe. will enable much wider dissemination than a national project would ever achieve.

B3.1.4 RELATION TO OTHER NATIONAL AND INTERNATIONAL RESEARCH ACTIVITIES

NOPTILUS builds on the experience gained by NOPTILUS partners from previous and currently running national and European research and development projects (in all of which at least some of the NOPTILUS partners have been involved). The following table presents a brief list of projects where NOPTILUS's partners have been involved and their relevance to the NOPTILUS project:

Participant	Project Name /Agency	Short Description/ Relation to NOPTILUS
CERTH **ETH Zurich**	SFLY/FP7 ICT	(ETH Zurich is the Coordinator) Real-time control and optimization of swarms of Micro Air Vehicles operating in highly uncertain and rapidly changing environments
CERTH	PEBBLE/FP7 ICT	(Coordinator) Real-time control and optimization for large-scale sensor/actuator networks for positive energy buildings
CERTH	AGILE/FP7 ICT	(Coordinator) Real-time control and optimization for self-tunable and re-configurable large-scale control systems
FEUP **MST**	C4C/FP7 ICT	Developing control for coordination of distributed systems for five case studies and in regard to control theory, communication networks, and computation. The case studies are: coordination of underwater vehicles, coordination of aerial vehicles, coordination of automated guided vehicles, coordination of a distributed complex machine, and design of a hierarchical control and command system for a motorway network.
FEUP	Underwater rendezvous of Aries and Isurus AUVs	The underwater rendezvous between the Aries and Isurus AUVs (in cooperation with UC Berkeley)

FEUP	SEACON	Demonstration and development of operations concepts with autonomous underwater vehicles.
FEUP	RAIA	Galicia-North of Portugal Oceanographic Observatory using AUVs
FEUP	NETVEHICLE	Framework for the systematic design and deployment of networked vehicle and sensor systems in novel applications with strong societal impact.
FEUP	EMEPC-UP	Under a MOU between Porto University and the Portuguese Task Force for the Extension of the Continental Shelf , researchers from FEUP are participating, since Sept 08, in oceanographic cruises, where they have been piloting the Deep-sea ROV[i] Luso.
ETH Zurich	muFly/FP6IST	(Coordinator) Designed of an optimized micro-helicopter of the size of a small bird, with integrated control, communication, perception and energy.
ETH Zurich	robots@home/FP6IST	Development of robotic navigation techniques optimized for indoor robots, with a view toward marketability.
ETH Zurich	BACS/FP6IST	(Coordinator) Study of the plausibility of Bayesian inference in biological systems from the molecular scale to the behavior of individuals or populations.
ETH Zurich	AIROBOTS/FP7ICT	Design and control of flying robots for structure inspection and manipulation
ETH Zurich	NIFTi/FP7ICT	Mapping and navigation in unstructured environment for Search and Rescue applications
ETH Zurich	URUS/FP6IST	Ubiquitous Networking Robotics in Urban Settings. Multi-robots, navigation and real-time control.
ETH Zurich	EUROPA/FP7ICT	European Robotic Pedestrian Assistant. Navigation and 3D mapping in urban environment
TU Delft	SPN/NWO-STW	Signal processing for self-organizing wireless networks
TU Delft	Smart PEAS/STW	Product quality control using Smart Process Environment Actuators and Sensors (PEAS) based Ultra Wide Band (UWB) technology
TU Delft	UCAC/EUROPA MOU ERG Nr1	UUV Covert Acoustic Communications
TSI	COOPCOM	Cooperative and opportunistic relay communications
TSI	U-BROAD	MIMO communications, channel modeling
TSI	Kouretes Robocup Team	Robocup team employing congitive-based and reinforecement leaning methods
TSI	RLcSL/IST/FP6	The "Reinforcement Learning via Supervised Learning" (RLvSL) project's goal is to investigate the potential of using Supervised Learning technology in order to improve Reinforcement Learning methods.
Imperial	BASIC/UK Research Councils	Reverse Engineering the human Vision system
Imperial	Underwater inspection and on land buried pipeline mapping/British Gas	Underwater inspection and on land buried pipeline mapping.
Imperial	EPSRC	3D surface reconstruction, with particular emphasis on 3D face reconstruction and recognition

MST	MARINE/INTERREG	Demonstrate the applicability of a set of underwater technologies as efficient tools to face maritime incidents.
MST	XTREME/QREN - SI I&DT	Development of a new series of Autonomous Underwater Vehicles with significant improvements in term of: mechanical reliability and efficiency, navigational results and capabilities for obstacles detection and avoidance.

Apart from the above-mentioned projects, NOPTILUS is strongly related to the EC-funded FP6 ICT projects GREX and VENUS and the FP7 ICT projects Co3-AUVs, TRIDENT, C4C and SHOAL that deal with underwater vehicles and related systems. As already mentioned in Section 1.1.1, the main difference/innovation of NOPTILUS is the development of a totally autonomous multi-AUV system equipped with automated situation understanding and decision-making capabilities. In other words, in all the aforementioned projects, the High-Level modules of Figure 1 are totally missing, with human operators taking over the tasks that the High-Level modules of NOPTILUS automatically handle. Apart from this key difference with the existing projects, NOPTILUS will advance significantly – as compared to the existing projects – all of the key technologies and modules involved in multi-AUV design: improved communication, sensing and localization systems by exploiting AUV “mating” and cooperation and “enriching” these systems with cognitive attributes, “seeing through murky waters” underwater vision systems, highly-accurate underwater map construction and process tracking techniques by combining machine learning, dimensionality reduction and advanced estimation methodologies, learning-based motion controllers for compensating with high efficiency and robustness strong currents and turbulences; Last but not least, the introduction – for the first time in an integrated multi-AUV system, to the best of our knowledge – of sensory-motor control for multi-AUV systems.

B3.2 Plan for the Use and Dissemination of Foreground

B3.2.1 PLANNED DISSEMINATION ACTIVITIES

To obtain as much dissemination of the project results as possible, several forms of **dissemination media** will be used to achieve that objective:

- Construction of a **NOPTILUS web site** that will contain information about the project's objectives, approach, project status, project sites, public deliverables, planned events, etc., and will be continuously extended and updated during the project's lifetime. The site will have both a public access area and a limited access area for the use of the Consortium to transfer information and facilitate file exchange.
- Preparation of a **NOPTILUS presentation leaflet** as well as a **short video** presenting the NOPTILUS concept at an early stage of the project, where the objectives, approach, and expected outcome of the project work will be presented in sufficient detail. The leaflet and the video will be used as a means to provide project information in public correspondence, conferences and similar events.
- **Scientific publications** in international reputable technical journals as well as publications addressed to practitioners and decisions makers in broadly read technical periodicals like IEEE Transactions on Robotics, Journal of Field Robotics, The International Journal of Robotics Research, Autonomous Robots, Robotics and Autonomous Systems, IEEE Journal on Oceanic Eng., IEEE Transactions on Pattern Analysis and Machine Intelligence, IEEE Control Systems Magazine, IEEE Communication Journals as well as journals and magazines related to underwater-related applications.
- Participation in international **conferences** such as the ICRA, IROS, RSS, ISRR, FSR, ISER, OCEANS, Underwater Communication Conferences, various Underwater Application

Conferences, etc as well as national conferences where appropriate. Organization of **workshops and special sessions** in the above-mentioned conferences.

- Participation in **AUV-related fairs and competitions**.
- Of special importance within NOTPILUS is the **Underwater Vehicle User Group,** which will consist of underwater application users, operators and authorities, AUV providers as well as all kinds of potential users of AUV systems (e.g. port authorities, rescue system operators) along Europe and worldwide. The user group members will be getting regular info/updates on the NOPTILUS achievements. They will be invited to participate at the 2 NOPTILUS workshops that will be organized especially for them and to the NOPTILUS open-fairs during demonstrations.
- At least one joint event – e.g. a joint workshop in an robotics conference – will be co-organized with EC-funded projects that are strongly related to NOPTILUS such as GREX, VENUS, Co3-AUVs, TRIDENT, C4C and SHOAL. The main focus of these joint event(s) (attempts will be made to have the first of these events on Y1 of the project) will be on joint actions and transfer of knowledge between the projects. As NOPTILUS is an Integrated Project, it will take the lead in coordinating the actions between all underwater robotics EC-funded projects and organizing the joint event(s).
- Made all possible efforts to establish cooperation with the EuRobotics and EuCognition coordinating actions, become members or cooperation partners of the two actions, participate to the events organized by the actions' consortiums and update their members/cooperation partners about the most significant advances of NOPTILUS.
- Preparation of a NOPTILUS CD-ROM with informative content regarding NOPTILUS's efforts, progress and results.
- **Course material** for universities to be used in interdisciplinary postgraduate (M.Sc. or Ph.D.) courses, summer schools, decision makers and consultants, as well as for SMEs on NOPTILUS technology. Two summer schools will be organized within NOPTILUS for young researchers as well as AUV system developers and (potential) users.
- **Open-house fairs** will be organized at the NOPTILUS's Test Case during demonstration, where visitors will have the opportunity to visit the Test Case and get to see the NOPTILUS system on operation.
- Last, but not least, direct participation of **project partners** in influential bodies involved in underwater-related applications, environmental monitoring, rescue operations, etc such as various international and national policy-making and standardization groups where NOPTILUS partners are either members or have direct influence.

The list of dissemination activities will be further developed and refined within the Dissemination and Use of Foreground, for which the first version is scheduled for month 6 of the project.

B3.2.2 USE OF AND CONTRIBUTIONS TO STANDARDS

The integration and demonstration of NOPTILUS system will be done according to IEEE Standard 1220-2005 for the systems engineering process.

The existing AUV infrastructure is partially compliant with STANAG 4586. Also at the current stage, MST and FEUP is working on appropriately adapting their infrastructure so that it complies with JAUS (Joint Architecture for Unmanned Vehicle) and Janus standards and on implementing DTN (Delay Tolerant Network) for underwater communications.

Apart from the above, all necessary efforts will be made within NOPTILUS for the development of **benchmarking** test cases where different researchers and developers involved in the underwater vehicles' community can test and evaluate their developments (e.g. new communication or sonar systems, new strategies for mapping or coordination between underwater and surface vehicles, new trajectory generation modules, etc). More precisely, detailed simulation models of all three basic NOPTILUS test scenarios operations will be developed, involving all operations, modules and phenomena involved and affecting the underwater operations (i.e. communications, localization, sonars, vision, control, AUV dynamics, and their interplay with the underwater environment as well as effect of underwater operations and phenomena to low-, medium- and high-level modules). The real-life data gathered during the testings will be used to calibrate and validate the simulation models in order to render them as realistic as possible. Finally, an open-source approach will be adopted in order to render these simulation models easily interface-able to modules and systems developed by non-NOPTILUS researchers and developers.

B3.2.3 EXPLOITATION PROSPECTS AND PLANS

NOPTILUS prospects of exploitation are solid, as it will be delivering a system that meets a very basic need of a wide range of underwater- and sea-related markets/users. The market for the NOPTILUS system that is most closely linked to the NOPTILUS developments and demonstrations will be (a) the developers and providers of AUVs and underwater sensors and communication systems, (b) port authorities. But, furthermore, a much wider market will consist of users, authorities and developers involved in search and rescue operations, oceanographic missions, sea-transport, environment-related bodies and organizations, the police, defense-related organizations, etc.

To maximize the NOPTILUS project's exploitation potential, the NOPTILUS Dissemination and Use of Foreground will ensure that the products and systems developed are advertised and commercialized according to each potential market's characteristics and exploitation potentials. Furthermore, the dissemination activities will reach out to the potential customers and developers of AUVs and beyond.

As a most basic NOPTILUS exploitation, the NOPTILUS's actively participating implementation site (APDL) is committed to adopt the NOPTILUS system (assuming that efficiency and cost-effectiveness is successfully demonstrated). APDL would then furthermore be keen to convince other port authorities it has close cooperation with, to deploy the NOPTILUS system within their port as well as to promote it among their colleagues in other authorities.

The system developers within NOPTILUS (research institutions and the SME MST) are strongly interested in exploiting the project's intermediate and end products and the obtained know how via licenses and future contracts. A particular role in this context has MST who will, in collaboration with the project coordinator, be the principal promoter and sales agent for the NOPTILUS system and intermediate products.

Among other actions to be detailed in the Dissemination and Use of Foreground, the following set of actions will be performed:

- A significant effort will be devoted by all partners so that potential users of NOPTILUS in Europe, the U.S.A. and elsewhere will adopt the NOPTILUS system. The NOPTILUS partners (especially FPU, MST, ETH Zurich and TU Delft) have established links with many users and operators of systems related to underwater applications all around the world, with many of these authorities and operators currently running systems developed by the aforementioned partners; the successful implementation and operation of these systems will be the main incentive for the aforementioned authorities and operators, as well as a convincing argument on behalf of NOPTILUS partners for the adoption of NOPTILUS to their systems.

- The participation of MST to the project will create business opportunities in the markets already addressed by it; Most importantly, it will open new fields of applicability for its products to applications where the use of AUVs is currently formidable such as operations that are currently accomplished by divers or applications with high-operational costs induced by the human-operators involved in operating the vehicles. Since NOPTILUS will provide a totally autonomous solution to systems where the strong involvement of the human-factor is currently required, it will enable formerly economically non-viable applications.
- Finally, for the low-level module developers (TSI, Imperial and TU Delft), their developed systems may be used beyond the AUV and underwater-related applications but be extended to more general applications of cooperative sensor and communication systems and vision systems.

To attract future investors, business plans will be developed and presented to companies and stakeholders in the energy-oriented sector.

Informal contacts in different situations, like conference, technical meetings, and presentations, will be used to spot exploitation opportunities that will be shared with the rest of the consortium members as one of the points in the agenda on the regular consortium meetings. The exploitation intentions and activities of NOPTILUS will be further refined and clarified during the project's lifetime and will be reported in the Dissemination and Use of Foreground.

B3.2.4 MANAGEMENT AND PROTECTION OF KNOWLEDGE

The partners shall take reasonable actions to protect the knowledge resulting from the project, according to their own policy and legitimate interest and in observance of their obligations under the EC Grant Agreement. The knowledge shall be the property of the partner carrying out the work leading to that knowledge. When several partners have jointly carried out work generating the knowledge and where their respective share of work cannot be ascertained, they shall have joint ownership of that knowledge. In this particular case, partners shall jointly apply to obtain and/or maintain the relevant intellectual property rights and shall strive to set up amongst themselves appropriate agreements in order to do so. The share of each contributor to the knowledge development shall be defined proportionally to the resources implemented by each, whether human, financial or intellectual.

The access rights to pre-existing know-how and knowledge will be thoroughly detailed in the Consortium Agreement. It will basically be treated with or without financial compensation on a case-by-case basis, by considering each party's interest. The IPRC (Section B2.1.2) will be in charge of the integrative management related to these issues (e.g. determination of ownership, management of joined ownership where applicable, granting of access rights, feasibility studies, patents or other protection). The IPRC will also be responsible for identifying the knowledge that could be the subject matter of protection, use or dissemination based on publications, reports and deliverables issued by WP Leaders. The IPR departments of each partner organization will be implied in this task and responsible for negotiating the property rights and patenting costs. The IPRC will continuously consult and take into account the expertise of the **IPR Helpdesk** of the EC.

IPRC will also take all necessary measures to appropriately balance the trade-off between dissemination of the results and protection of knowledge. For instance, if a particular methodology or technology developed within NOPTILUS is decided to be patented, the IPRC may decide to ask the EC to temporarily change the dissemination level of the deliverables describing it to Confidential (CO) until all necessary steps for the protection of knowledge are completed.

In general, the consortium will seek to maximize the **protection of the intellectual property** and other results generated by NOPTILUS for individual, joint and European advantage. The partners will carefully consider the appropriate vehicle for protection of intellectual property rights on a case-by-case basis. The inventing partner or partners will bring to the IPRC's attention every intention to protect (or share) the intellectual property generated during the course of the Project. The Consortium Agreement will set out these provisions legally and in more detail, but the key concrete elements of the process are set out below.

- Intellectual property created by the consortium during the project will be exploited for maximal value via a number of different routes. The most appropriate route will be chosen on a case-by case basis but could include a patent protection or licensing of software produced during the project.
- The knowledge generated during the project will be captured and made available to project members who need to know in a timely and appropriate fashion.

At the time of the proposal, none of the partners has identified the need for patenting any of the results obtained. However, the possibility of intellectual protection via a patent will be always open in the project. In that case, the inventing partner or partners will bring to the attention of the IPRC for consideration every intention to protect (or otherwise) the intellectual property generated during the course of the Project. If the inventing partner(s) do not intend to seek a patent, then if another partner (or partners) informs the notifying partner and IPRC in writing within one calendar month of such notice that it wishes to obtain or maintain such protection, the notifying partner shall assign to such other partner(s) all necessary rights which it owns. In case of any disputes, which are not re-solvable within the consortium, the partners may appeal to an IPR Council. Partners may agree to jointly apply to obtain and/or maintain intellectual protection. The partners concerned shall seek to agree amongst themselves arrangements on a case-by-case basis. So long as any such right is in force, each Partner concerned shall be entitled to use and to license such right without the consent of the other partners. In case of licensing to third parties, appropriate financial compensation shall be given to the other partners concerned.

B3.2.5 RISK ASSESSMENT AND RELATED COMMUNICATION STRATEGY

Risks to Society through NOPTILUS developments

There are no worth-noticing risks to society from NOPTILUS developments

Risks to the People Involved

Severe weather conditions may put the safety or life of the people involved in the NOPTILUS tests in danger. The rich experience of all 3 Portuguese partners in performing tests of similar nature in the past provides a guarantee for the minimization of such risk. In particular and based on their experience the 3 Portuguese partners will decide, in case of severe weather conditions, if a particular test should or should not start or even if it should be terminated while in progress.

Moreover, all tests will be designed and executed according to standard procedures that are applied to similar tests in the NOPTILUS test case many years now (e.g. maximum time and depth the divers should operate, minimum distance between divers and AUVs, continuous monitoring of AUVs by human operators who will perform emergency stopping in case of dangerous situations, etc).

Risks to Sea Fauna and Flaura

There is no risk or danger from NOPTILUS developments and tests to the sea fauna and flaura. In particular, the NOPTILUS tests will employ "environmental friendly" chemicals such as ink, rhodamine and/or fish oil that cause no damage to the underwater environment. Moreover, the health or life or fish and other sea-animals (such as dolphins) will not put at stake as the sonars used in the NOPTILUS AUVs cause no harm to them (low power sonars).

Risks to Successful Completion of the Project

Significant risks and contingency plans have been already identified and for each one a possible contingency solution has been selected; see Appendix A for more details.

GENDER ASPECTS

It is increasingly recognized that gender equality is a human rights issue and a necessary criterion for achieving sustainable and people-centered development. Women are often the first to be affected when job opportunities are lacking and more women than men are unemployed. Efforts must be made at a European level to promote gender integration into research where the woman total rate of participation is particularly unsatisfactory. The Organizations participating in NOPTILUS fully comply with legislation concerning gender equality and supports both genders' participation and collaboration by both genders in its research activities. No gender differences are made in NOPTILUS and all the aspects of the research can be similarly conducted by women and men. There is no logical reason why women should not work in this area, and if NOPTILUS succeeds in attracting a larger proportion of women students and young researchers to the project, the result will be more qualified female staff working in the domains of underwater systems and robotics.

Finally, it is noticed that one of the leaders of the partner Imperial has been a female senior researcher (Professor Maria Petrou).

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APPENDIX A: RISK ASSESSMENT

Management-related risks

Description:	**Consortium involves many and diverse participants to be easily coordinated**
Impact:	High
Risk:	Low
Evaluation:	Should this problem occur its impact on the project would be significant. The risks are low, as all partners involved have extensive experience and background in the implementation of National and European Projects.
Resolution:	The steering committee comprises a small number of people and has the flexibility, efficiency and operability to successfully take decisions regarding the project.

Description:	**Consortium has no harmony**
Impact:	High
Risk:	Low
Evaluation:	There are many reasons to believe that partners and individuals will cooperate harmoniously - ranging from a record of successful past collaboration between individuals and organizations, to personal friendships developed over the course of collaboration. Such problems may arise when the plan of activities is not fully understood by all participants or personal incompatibilities arise during the work.
Resolution:	Team building and social events for strengthening the interaction and mutual respect of the people working in this project will be an integrating part of the project meetings and integration weeks. The project coordinator will continuously be in contact with the partners and will visit them regularly. This guarantees that team problems are identified and solved before they escalate.

Description:	**Poor quality of deliverables and delay in meeting the deadlines**
Impact:	Medium
Risk:	Low
Resolution:	The progress of the project will be assessed at frequent intervals to predict possible delays and to act accordingly.

Description:	**Staffing & Recruitment Problems**
Impact:	Low
Risk:	Medium
Resolution:	The consortium members have access to highly qualified engineering researchers and professionals, through graduate school contacts and professional networks. Staffing risks will be mitigated by advertising early and maintaining contact with potential replacements from the beginning till the end of the project. The quality and visibility of the partners ensures steady interest in terms of highly qualified graduate students and post-docs to engage in research projects.

Technology/Methodology-related problems

Description:	**The complexity of implementation compromises system performance**
Impact:	High
Risk:	Low
Resolution:	Integration of all modules will be of central focus during the early development stages to ensure that potential bottlenecks related to the complexity of implementing the whole system are addressed early on. Furthermore, all members of the consortium have substantial experience in projects and implementations of the NOPTILUS scale and complexity. Therefore, the likelihood that such problems will compromise the project is low.

Description:	**Plans prepared at the end of each work package may be missing important points**
Impact:	Low
Risk:	Low
Resolution:	To assure that the work packages will be executed correctly, assessment of the risk plans for each of the work packages will be made again before they start.

Description:	**Unavailability of technology**
Impact:	Medium
Risk:	Low
Evaluation:	Most of the core components required for implementation are already available (commercial off-the-self). Also, for components required for realizing the MIMO communications and sonar-based sensing, a specific evaluation and impact assessment plan - based mostly on simulation investigations - will be developed and delivered in the 2nd reporting period of the project.

Description:	**Technology changes require redesign**
Impact:	High
Risk:	Low
Resolution:	Technological changes are expected to leverage rather than impede the work planned. Apart from this, technology watch is a key project activity. The Steering Committee will continuously monitor external developments and use them to re-plan if necessary.

Description:	**Functional and interoperability issues between the various components that comprise the NOPTILUS system and the interfaces required for its implementation in the Test Case**
Impact:	Medium
Risk:	Medium
Resolution:	Task WP2.1 has been defined to mitigate associated risks. The consortium will inspect possible technical inconsistencies and a resolution will provided according to the best available solution. Moreover, all the systems and components that will be employed within the NOPTILUS system will be of open architecture so as to minimize the risk of interoperability problems. Partners FEUP and MST have extensive experience in the design and deployment of such systems.

Description:	**Time-consuming operations lead to non-real time response of the NOPTILUS system.**
Impact:	Medium
Risk:	Low

Resolution:	All NOPTILUS modules are highly scalable and the responsible partners for developing these modules have a proven experience in developing scalable systems for large-scale applications. Moreover, the modules of NOPTILUS that "consume" most of computational power (e.g. the PAN module) allow the user to "tune" their computational requirements (at the expense of affecting performance). Alternatively, most of the "consuming" computations will take place centrally (at the NOPTILUS control centre) at the expense of sacrificing the distributed-computation nature of NOPTILUS.

Description:	**A particular low- or medium-level module does not provide the required accuracy or efficiency**
Impact:	High
Risk:	Low
Resolution:	The proposed solutions for these modules in most cases offer a range of accuracy and efficiency levels that can be traded to meet the required levels of operation in all modules. In addition, all partners responsible for the development of these modules have significant experience in the development of systems of similar nature, complexity and scale. Therefore, the likelihood that such problems will compromise the project is low.

Description:	**An optimized AUV communication system cannot be developed.**
Impact:	High
Risk:	Low
Resolution:	TU Delft has both theoretical and hands-on experience in developing communication systems for underwater vehicles and networks. Many different options will be considered for the improvement of the reliability and bandwidth of underwater communications. Failure to successfully apply one of these options will not be detrimental to this particular objective.

Description:	**The (vision, communication, etc.) modules to be installed cannot be integrated on the AUVs.**
Impact:	High
Risk:	Low
Resolution:	The required technology is mostly available off-the shelf. Partner MST has extensive experience in the integration of such modules on AUVs.

Description:	**The techniques such as exploiting swarm motion, etc employed in the localization module fail to provide the desired accuracy**
Impact:	Medium
Risk:	Low
Resolution:	In such an unlikely event, the NOPTILUS localization module will focus on employing re-surfacing techniques which can always provide the desired accuracy.

Description:	**The MIMO-based sensing methods fail to provide the desired accuracy**
Impact:	Medium
Risk:	Low
Resolution:	Standard SISO sonar-based techniques will be employed in such a case at the expense of not

	providing the intended accuracy of the MIMO NOPTILUS sensing system.

Description:	**The "seeing-though-murky-waters" vision system fails**
Impact:	High
Risk:	Low
Resolution:	The possibility of such an event to happen is negligible as the partner responsible for developing the system (Imperial) has a significant past experience in the development of such systems. However, in the unlikely event that the "seeing-through-murky-water" systems fails, underwater vision systems developed in the past by Imperial – and successfully implemented in underwater missions – will be further developed and enhanced in order to be deployed within the NOPTILUS system.

Description:	**The cooperative distributed estimation module fails to provide the desired accuracy or efficiency**
Impact:	High
Risk:	Very Low
Resolution:	There exists no possibility of such an event to take place. The cooperative distributed estimation module will consist of a combination and integration of methodologies and techniques that have been successfully applied in other applications in the past.

Description:	**The learning-based motion control module fails**
Impact:	High
Risk:	Low
Resolution:	The learning-based control techniques to be employed in the motion control module of NOPTILUS have been successfully implemented in the past in a vast majority of real-life applications and, therefore, the probability of such an event is negligible. However, in the unlikely case that such an event happens, the NOPTILUS module will employ the standard, non-adaptive motion control module mentioned in WP5 description.

Description:	**The sensory-motor control module fails to provide with the desired accuracy**
Impact:	High
Risk:	Low
Resolution:	In such an unlikely event, the NOPTILUS system will employ only the motion control module by focusing on enhancing its localization techniques and methodologies

Description:	**The situation understanding module faces with cases "not-learned-in-the-past"**
Impact:	High
Risk:	Low
Resolution:	In cases where no "rich" past data are available or in case of unforeseen events, the NOPTILUS methodology for recognizing dynamic events will not be always possible to recognize dynamic events in which case human intervention will be required. However, most of the events identified so far are common to all underwater missions and a rich amount of past data is available for such events. Moreover, even in the case where human intervention will be required, such an intervention will be "minimum" and no advanced and complicated human actions will be required that vitiate the fully-autonomous nature of NOPTILUS.

Description:	**The NOPTILUS PAN module fails to provide with trajectories that provide optimal situation understanding**
Impact:	High
Risk:	Low
Resolution:	In such an unlikely event, the PAN module will be employed only for optimizing estimation accuracy. The methodologies employed within NOPTILUS PAN module have proved in the past to provide with extremely high accuracy and efficiency in applications where the objective is to provide optimal estimation accuracy (e.g. in mapping, exploration and target tracking applications).

Demonstration-related problems

Description:	**System performance during demonstration is so poor that leads to potential hazards**
Impact:	High
Risk:	Low
Resolution:	All operational aspects will be recorded and continuously monitored by human operators so that the NOPTILUS system can, if necessary, be manually overridden, while system developers have the chance to investigate how a repeat of such performance deterioration can be prevented.

Description:	**Demonstration delayed or failed due to last-minute hardware failures, unavailability of demonstration site or incompatible weather.**
Impact:	Medium
Risk:	Low
Resolution:	The team will have the integration weeks to practice the operational scenarios. Furthermore, the demonstration schedule and logistics will take into account the possible requirement of a second trial time in the case of adverse weather conditions. Finally, a strategy for procurement of spare parts will be envisaged, within the limits of available budget.

Description:	**One or more of NOPTILUS modules fail to provide the required accuracy or efficiency**
Impact:	High
Risk:	Low
Resolution:	In such an unlikely event and depending on the particular module that does not “work properly”, the NOPTILUS consortium will take mitigation measures mentioned in the previous section “Technology/Methodology-related Risks”.

Description:	**One or more of the components of the overall NOPTILUS system is malfunctioning or even totally fails during demonstrations (e.g. an AUV loses communication or even gets lost)**
Impact:	Medium
Risk:	Medium
Resolution:	One of the main reasons the NOPTILUS Situation Understanding module will be developed is in order to take care of such situations. More precisely, in case of a severe malfunction of system

	components, the NOPTILUS Situation Understanding module will re-design the NOPTILUS overall optimization logic in such a way that the particular mission's objective is fulfilled by employing only the components of the system that are properly operating.

Description:	**Problems in proper interfacing and cooperation between the different NOPTILUS layers (low, medium and high)**
Impact:	High
Risk:	Low
Resolution:	NOPTILUS' software components will be extensively tested – using the detailed simulation environment – before demonstrations to make sure that they properly cooperate. Moreover, to minimize the possibility of improper interfacing/cooperation due to a hardware/middleware problem, all NOPTILUS components will be mounted on the existing multi-AUV platform which allows for the easy replacement of components that are not properly working by existing ones (e.g. replacement of NOPTILUS' modems or sonars by the existing ones) at the expense of not providing the intended efficiency.

Description:	**Problems during the execution of demonstrations prevent their proper completion (e.g. sunken drums are washed away by strong currents)**
Impact:	Medium
Risk:	Low
Resolution:	NOPTILUS will take all necessary measures in the beginning of each test to make sure that weather and other environmental conditions will not have a destructive effect to the test. Apart from this, in case a particular test is not accomplished successfully due to environmental or other external reasons it will be repeated again.

Exploitation Risks

Description:	**Non correspondence with market demand**
Impact:	Medium
Risk:	very low
Evaluation:	The project has been developed with the goal of advancing technology in the field of AUVs. There is significant interest in this research area and many potential applications of interest and relevance to the market.
Resolution:	During the later stages of the project lifecycle, adherence of the product to the identified market needs will be constantly monitored. MST has significant experience in the market segment of AUVs for oceanographic surveys, environmental monitoring and security applications. APDL as the end-user have specific needs that will be communicated to the other project members through the communication and integration strategies to be implemented as outlined in the proposed management plan. Their input, from the side of both the developers and end-users, will ensure relevance of the developments.

Description:	**Difficulties in handling the IPR issues**
Impact:	High
Risk:	Low
Resolution:	In NOPTILUS special emphasis is given on IPR issues, the basic principles on IPR handling and

	protection are outlined in Section B3.2.4 of this proposal. As part of the Project Management structure the IPR Committee is a body dedicated to the handling of IPR Issues, conflict-management and the assistance of PC on IPR-related issues. The consortium agreement, to be signed before the start of the Project, will detail procedures related to IPR and IPR-handling.

Description:	**Non-competitiveness due to increased deployment and operational costs**
Impact:	High
Risk:	Low
Resolution:	The use of readily available modules ensures a solution that will be competitively priced. The proposed algorithmic and methodological developments (e.g. better communication systems) will leverage existing solutions. The AUV market is currently a niche market and should such risks be realized, the partners will investigate a service-based marketing model or even provide to end-users a set of independent and interoperable modules (e.g. a communication module, a localization module) and retort to known ("simpler" but worst-performing) solutions. Also the risk for increased operational costs are very small given that optimization (e.g. for path planning and navigation) are at the core of the Project.

Description:	**The Project fails to achieve some of the objectives and therefore no concrete "product" is available**
Impact:	Low
Risk:	Very Low
Resolution:	At the center of the efforts in the NOPTILUS project is the integration of various components and applications in concretely-defined cases. Should integration fail, each of the modules to be developed have solid exploitation potential as standalone solutions to long-standing problems in their respective areas. The WP9 leader will identify exploitation opportunities for each of the modules and the research results, in tandem with exploitation for the complete system.

Description:	**Conflicting views on development between academics, end-users, and SME participants yield results that have little or no exploitation potential**
Impact:	High
Risk:	Low
Resolution:	The definition of concrete test cases, that the NOPTILUS system will be deployed and field tested, mitigates such risks. The common goal of achieving practical and realistic performance objectives will act as a mortar unifying differing views. Effective conflict resolution strategies will help reconcile such detrimental differences, should they occur.