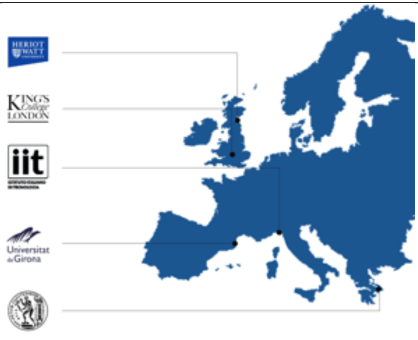
Pandora
Persistently Autonomous Robots

Heriot-Watt University Istituto Italiano di Tecnologia Universitat de Girona King's College London National Technical University of Athens	 www.persistentautonomy.com	Reference Code: Pandora-D5.5.3

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Persistent Autonomy through Learning, Adaptation, Observation and Replanning

DELIVERABLE 5.5.3:
S&T Objectives Performance Benchmarking Final Report

Distribution:	Pandora Partners, Project Officer, Reviewers
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Executive Summary

The goal of this deliverable is to detail the work done in the project corresponding to benchmarking and performance assessment. The technologies developed in the project have been tested in some scenarios which are very specific and cannot be really compared with any benchmark. The scenarios described in the project could represent a benchmark for future research projects. Therefore, the work presented in this deliverable is more related to the measurement of the performance itself for future comparisons. The report describes the work done in task WT5.4 for addressing the performance assessment of the project. It indicates also the list of indicators that were analysed in the final validation experiments, summarising the most important results and relating the performance to the Technology Readiness Level of each developed technology. Finally, it relates the final performance measures with the metrics proposed in the project to assess the performance of the S&T Objectives. This deliverable was not intended as a detailed report for describing the obtained results. Deliverable "D5.5.2 Validation Experiments - Reports and Demonstration" includes in detail the description of 27 final experiments as short reports, including its relation to the addressed S&T Objectives and performance assessment. We consider that D5.5.2 is the complete final report about experimentation, technological achievements and performance assessment, and this deliverable is only a complementary report for analysing the work done about benchmarking and performance assessment in Pandora project.

Performance assessment

Performance evaluation of all technologies developed in Pandora project has been a priority. WP5 had the task "WT5.4 Performance Assessment" which had the goal of measuring the success of all validation experiments that were carried out in each scenario to characterise and benchmark the scientific contribution of the project. This task started with some delay on month 25 (January 2014) instead of month 22. The important experimental work conducted for all scenarios at the end of 2013, delayed the beginning of the task. From month 25 till 27 (January till March 2014) a proposal of benchmarking and measuring the performance was conducted and proposed during the 2nd year review. The proposed benchmarking was inspired by the euRathlon European FP7 project, in which an important work had been done for benchmarking a set of teams participating in robotics competitions. Basically, the proposal consisted on grading different physical measures in which the experiments could be accomplished and then evaluating the performance of teams based on these grades. An example of such approach applied to Pandora's valve turning scenario was presented. The general conclusion was that more specific metrics to Pandora's scenarios should be used and also some measures of success in different conditions should be estimated. Another important point was to find out the indicators that were more relevant for industry, since industry would be more interested in measuring the possibilities of success of new fundamental concepts rather than measuring the robustness or industrialisation level. Also, other important points recommended during the 2nd year review, that were followed during the last year of the project, were: integration of all partner's work; persistent missions having planning to accommodate to different situations; perturbations and real conditions; improved algorithms and faster executions.

After the 2nd year review, a meeting with the Industrial Advisory Board (IAB) took place in which very useful advices were given to Pandora's partners. Industry was not interested in performing experiments deep, or in moving the vehicle fast, or during a lot of time, or even in performing experiments at sea. The interest of industry resides in evaluating if new technologies are ready to be industrialised. Performance measures must be related with Technology Readiness Levels, in the sense that it has no sense to evaluate maximum depth or water currents for low TRLs in which the goal is only a prove of concept. Therefore, they were interested in aspects such as:

- efficiency
- repeatability
- resilience
- reliability, long scenario
- statistical tests on success and repeatability
- robustness from disturbances (currents, perturbations,...)
- scalability (bigger environment, longer task, ...)
- software robustness
- computer power
- degree of dynamic environments

Pandora consortium prepared the last year of experiments considering these important metrics from IAB and also recommendations from reviewers. Each partner prepared a set a representative experiments to lead, in which performance was evaluated. During last months of the project, from month 33 till 41 (September 2014 till May 2015), experiments were performed in all 3 scenarios and some of these metrics were evaluated. We believe that the final procedure for evaluating the performance of Pandora's final results was correct and it will be useful for future related work and benchmarking.

In the final representative set of experiments, which are reported in Deliverable "D5.5.2 Validation Experiments - Reports and Demonstration", special emphasis was taken for evaluating and benchmarking the obtained results. From the 27 reported final experiments, many indicators were used and evaluated, considering the recommendations of IAB and reviewers. Figure 1, indicates the list of performance indicators that were considered in each final experiment. For details on each of the indicators and obtained results, reader should refer to Deliverable "D5.5.2 Validation Experiments - Reports and Demonstration", in which a short report (between 4-8 pages) details the context of the experiment and the obtained results. A summary of most representative performance indicators can be found in Figure 2, in which aspects such as accuracy, success, error, time or computer power are indicated. This list of indicators summarises the experimental achievements of the project.

When analysing the performance indicators to be considered, as indicated by the IAB, the Technology Readiness Level (TRL) has to be taken into account, to correctly choose the aspects that are relevant at each TRL. TRLs originate in the space technology sector, and are used by US and European public authorities, in the oil and gas industry and now in some parts of H2020 work programme. TRL describes the progression of a technology, product or service in terms of its proven availability and suitability to a particular application or market. TRL is measured on a scale of 1-9 with high numbers indicating close to market maturity and low numbers indicating a status further from market realisation. A technology, product or service will typically progress sequentially through the levels, prior to market entry. In Pandora project, the H2020 definition of TRL was followed, see Table 1, having an average of TRL between 5 and 6. Table 2 indicates the estimated TRL in each representative technology that was developed and experimented.

FINAL EXPERIMENT		PERFORMANCE ASSESSMENT
Scenario 1 experiments - Structure Inspection		
1.1	Planning for Structure Inspection	Plan quality, planner, planning time, TRL,
1.2	Robust Motion Control of Nessie VI	Error in steady state
1.3	Fault management	Accuracy, repeatability, valid pose, computer power, TRL
1.4	Focus of Attention	active vs passive
1.5	Autonomous Structure Inspection	Accuracy, repeatability
Scenario 2 experiments - Chain inspection and Cleaning		
2.1	Horizontal Chain Detection and Following with FLS	Percentage of detected links, accuracy, following success and detection vs chain layout, speed, TRL
2.2	Chain mapping with FLS mosaicing	Mosaic self-consistency, SNR improvement, map resolution and precision, computational power/time, TRL
2.3	Vertical Chain Detection and Following with FLS and multibeam sonar	Accuracy with MB and FLS, success rate, following speed, TRL
2.4	Chain cleaning with water jet	TRL
2.5	AUV control with water jet perturbation	Tracking error
2.6	Opportunistic Planning	Potential additional goals, plan quality, planner, planning time, TRL
2.7	Horizontal and vertical chain inspection at sea	Percentage of detected links, accuracy, following success and detection vs chain layout, speed, Accuracy with MB and FLS, success rate, following speed, TRL
Scenario 3 experiments - Valve turning		
3.1	Vision-based panel and valve detection	Accuracy, repeatability, valid orientation and pose, computer power, TRL
3.2	EKF - SLAM localization filter	Navigation error, computer power, TRL
3.3	Learning by demonstration for valve turning	Similarity, success rate, resiliency, accuracy, task scalability, computer power, TRL
3.4	Temporal Planning for Valve Turning Scenario	Plan quality, planner, planning time, TRL
3.5	Reactive behaviour learning for valve turning	Similarity, task scalability, computer power, TRL
3.6	Contact state estimation using force/torque sensor	Correctness
3.7	Combined long term experiment in water tank	Correctness, accuracy, performance, computer power, TRL
General experiments		
4.1	PHD-SLAM localization filter	Navigation error, computer power, TRL
4.2	AUV Online and Offline dynamic model identification	Fitting score
4.3	Control of Underactuated Underwater Vehicles	Tracking error
4.4	A Methodology for Interaction Control:Design of a UVMS Motion Control Scheme	Pose achievement
4.5	Servoing Control Methodologies for UUV Hovering around Large Pitch Angles	Pose achievement
4.6	Plan-Based Policy Learning	Efficiency, TRL
4.7	Planning and Persistent Autonomy	Replanning number of times, duration, scaling of planner, lost goals, TRL
4.8	Thruster failure recovery using reinforcement learning	Optimization method and computational cost

Figure 1: List of performance indicators that have been taken into account in each of the 27 final experiments of the project. Description and obtained values are detailed in deliverable D5.5.2.

FINAL EXPERIMENT		*PERFORMANCE ASSESSMENT*	*RESULTS*
Scenario 1 experiments - Structure Inspection			
1.1	Planning for Structure Inspection	Planning time	<10s
1.2	Robust Motion Control of Nessie VI	Error in steady state without external perturbations	<5cm, <5deg
1.2	Robust Motion Control of Nessie VI	Error in steady state with external perturbations	<8cm, <10deg
1.3	Fault management	Residual error in detecting thruster states	10%
1.3	Fault management	Computer power (single-core 32 bits Intel Atom processor 4GB	22%
1.4	Focus of Attention	Mean square error	<0.5m
1.5	Autonomous Structure Inspection	Pillar detection success	80%
Scenario 2 experiments - Chain inspection and Cleaning			
2.1	Horizontal Chain Detection and Following …	Percentage of detected links	91.5%
2.1	Horizontal Chain Detection and Following …	Accuracy of link detection	7.57cm
2.1	Horizontal Chain Detection and Following …	Following success	95%
2.1	Horizontal Chain Detection and Following …	Chain following speed	0.05m/s
2.2	Chain mapping with FLS mosaicing	SNR improvement	7 times
2.2	Chain mapping with FLS mosaicing	Map resolution	1 mm
2.2	Chain mapping with FLS mosaicing	Error in groundtruth measures	8%
2.2	Chain mapping with FLS mosaicing	Computation time per registration	60ms
2.3	Vertical Chain Detection and Following …	Accuracy of chain detection with MB	5 cm
2.3	Vertical Chain Detection and Following …	Chain detection with MB success	100%
2.3	Vertical Chain Detection and Following …	Chain folowing speed	0.1m/s
2.5	AUV control with water jet perturbation	Tracking error	<10cm, <5deg
2.6	Opportunistic Planning	Planning time	<10s
Scenario 3 experiments - Valve turning			
3.1	Vision-based panel and valve detection	Accuracy of panel detection (at 3m, 1.5m and 0.5m)	9cm, 2.3cm, 0.3cm
3.1	Vision-based panel and valve detection	Accuracy or valve orientation	10.8 deg
3.1	Vision-based panel and valve detection	Valve orientation success	95%
3.1	Vision-based panel and valve detection	Computer power (ULV dual core 32 bits intel processor 2GB RAM)	61%
3.2	EKF - SLAM localization filter	Navigation error	<1.5 m
3.2	EKF - SLAM localization filter	Computer power (Intel Core i7 CPU 870 2.93GHz 8 GB RAM)	10%
3.3	Learning by Dem. for valve turning	Success rate without perturbations	87,50%
3.3	Learning by Dem. for valve turning	Success rate with 70% of perturbation	50%
3.3	Learning by Dem. for valve turning	Accuracy without perturbation	<7cm
3.3	Learning by Dem. for valve turning	Accuracy with perturbation	<16cm
3.3	Learning by Dem. for valve turning	Computer power (Intel Core i7 CPU 870 2.93GHz 8 GB RAM)	2%
3.4	Temporal Planning for Valve Turning	Planning time	<2s
3.6	Contact state estimation using force/torque …	Correctness	72%
3.7	Combined long term experiment in water tank	Duration time	>3h
3.7	Combined long term experiment in water tank	Valve turning attempts	37
3.7	Combined long term experiment in water tank	Failed attempts	10,80%
General experiments			
4.1	PHD-SLAM localization filter	Navigation error	<0,5m
4.1	PHD-SLAM localization filter	Real time computation	No
4.2	AUV Online and Offline dynamic model	Fitting score	72,50%
4.3	Control of Underactuated Underwater	Tracking error	<10cm
4.7	Planning and Persistent Autonomy	Planing time verus execution time	<2%

Figure 2: Summary of obtained results in most relevant performance indicators of the project.

Table 1: Technology Readiness Level definition according to H2020 work programme

TRL	H2020 description
1	Basic principles observed
2	Technology concept formulated
3	Experimental proof of concept
4	Technology validated in lab
5	Technology validated in relevant environment
6	Technology demonstrated in relevant environment
7	System prototype demonstration in operational environment
8	System complete and qualified
9	Actual system proven in operational environment

Table 2: Technology Readiness Levels achieved in the developed technologies of the project

Project technologies	*TRL*
Fault management	5
Horizontal chain detection and following	5
Chain mapping with acoustic mosaic	6
Vertical chain detection & following	5
Chain cleaning with water jet	3
Opportunistic planning	4
Chain inspection at sea	6
Vision-based panel detection	6
Vision-based valve orientation detection	5
EKF-SLAM localisation filter	7
LbD for valve turning	5
Reactive behaviour learning	5
Valve turning long-term experiment	6
PHD-SLAM localization filter	4
Planning and persitent autonomy	4

S&T Objectives benchmarking

Pandora proposal contained the achievement of 16 S&T Objectives related to "THEME A: Describing the World", "THEME B: Directing and Adapting Intentions" and "THEME C: Acting Robustly". Work packages were in charge of addressing all them and demonstrating its achievement in the final validation experiments of the project, deliverable D5.5.2. Figure 3 relates each objective with the list of final experiments that evaluated them. As it can be observed, all S&T Objectives were successfully addressed in one or more final experiments of the project.

Additionally, the proposal included for each S&T Objective some measures to assess its performance. The performance assessment related in the previous section has tried to follow these proposed performance assessment metrics, although in some occasions it has been difficult to achieve. Table 2 to 17, relate for each S&T Objective, the proposed performance assessment metrics, and the performance indicators taken into account in each final experiment that addressed the S&T Objective. It can be observed that performance indicators in most of the occasions measured things that were similar to the ones proposed in the Pandora project proposal. We conclude then, than the performance of most S&T Objectives was correctly addressed by the performance assessment done in the final validation experiments. As stated before, for details on the performance assessment, reader should refer to Deliverable "D5.5.2 Validation Experiments - Reports and Demonstration", which relates the results of each experiment with the corresponding S&T Objectives and performance indicator.

S&T OBJECTIVE		FINAL EXPERIMENT
S&T1.1	To incorporate a Bayesian probability framework in ontology representation, including propagation during reasoning and consistent adaptation of the ontology.	1.5
S&T1.2	To use sonar and video data to detect features on an underwater structure while moving and correctly match these to an already known workd model (geometric and semantic) thus localising the vehicle.	2.1, 2.2, 2.3, 2.4, 2.7, 3.1, 3.2, 3.7, 4.1
S&T1.3	To use inconsistencies in matching to update errors in the assumed geometric description of the world. To update the semantic (ontology) probabilities that describes the likely geometric and other relationships in this world.	1.5
S&T1.4	To diagonse the state of task execution based on status data from the execution layer and the world model, and to maintain the ontology describing the possible effects of action and the current task status.	1.3, 3.6
S&T1.5	With the assistance of the planner, autonomously direct the attention of sonar and video sensors to appropriate places in the work-volume, to provide needed world updates.	1.4, 1.5, 2.1, 2.3, 2.7, 3.7
S&T2.1	Extend hindsight optimisation planning to metric domains	4.6
S&T2.2	Develop plan repair and adaptation techniques, including opportunistic adaptation without sacrificing key commitments.	1.1, 1.5, 3.4, 3.7, 4.7
S&T2.3	Support plan-fragment insertion to enable the AUV to take advantage of unexpected opportunities when resource availability allows.	2.6, 4.7
S&T2.4	Enable extensions and updates to the planner's world model.	1.1, 1.5, 3.4, 4.7
S&T3.1	Develop imitation learning and reinforcement learning algorithms to learn PHMM representations of skills, including both synthesis and recognition of skills.	3.3, 3.5, 3.6, 3.7
S&T3.2	Develop covariance analysis method for reinforcement learning toa chieve robust skill execution in noisy unstructured underwater environment.	4.8
S&T3.3	Develop reinforcement learning with multidimensional reward for speeding up the robot skill leaning process.	4.8
S&T4.1	To develop a robust control module to act as an interface between the high-level modules and the hardware of the UUV platform	2.1, 2.3, 2.4, 2.7, 3.7, 4.4
S&T4.2	To develop robust UUV motion control methodologies compensating for the disturbances emanating from the environment.	1.2, 1.5, 2.5, 4.2, 4.3, 4.4
S&T4.3	To develop interaction control methodologies to implement interaction forces and torques needed to realice a task.	4.4
S&T4.4	To extend the operation envelope of a UUV by developing a sensor based control scheme, enabling it to perform as an almost 360º pitch sensor for inspection of surfaces independently of their orientation.	4.5

Figure 3: 16 S&T Objectives addressed by the project related to the 27 final experiments of the project. All objectives were taken into account in one or more final experiment.

S&T Objective	*Performance Assessment*
S&T 1.1 To incorporate a Bayesian probability framework in ontology representation, including propagation during reasoning and consistent adaption of the ontology.	**Correct propagation of uncertainty and Consistency of ontology**
Experiment	*Performance indicators*
1.5 Autonomous Structure Inspection	Accuracy, repeatability

Table 3: Experiments and performance indicators related to S&T 1.1

S&T Objective	*Performance Assessment*
S&T 1.2 To use sonar and video data to detect features on an underwater structure while moving and correctly match these to an already known world model (geometric and semantic) thus localising the vehicle.	**Correct detection, tracking and matching of features; Accuracy of vehicle localisation.**
Experiment	*Performance indicators*
2.1 Horizontal Chain Detection and Following with FLS	Percentage of detected links, accuracy, following success and detection vs chain layout, speed, TRL
2.2 Chain mapping with FLS mosaicing	Mosaic self-consistency, SNR improvement, map resolution and precision, computational power/-time, TRL
2.3 Vertical Chain Detection and Following with FLS and multibeam sonar	Accuracy with MB and FLS, success rate, following speed, TRL
2.4 Chain cleaning with water jet	TRL
2.7 Horizontal and vertical chain inspection at sea	Percentage of detected links, accuracy, following success and detection vs chain layout, speed, Accuracy with MB and FLS, success rate, following speed, TRL
3.1 Vision-based panel and valve detection	Accuracy, repeatability, valid orientation and pose, computer power, TRL
3.2 EKF - SLAM localization filter	Navigation error, computer power, TRL
3.7 Combined long term experiment in water tank	Correctness, accuracy, performance, computer power, TRL
4.1 PHD-SLAM localization filter	Navigation error, computer power, TRL

Table 4: Experiments and performance indicators related to S&T 1.2

S&T Objective	*Performance Assessment*
S&T 1.3 To use inconsistencies in matching to update errors in the assumed geometric description of the world. To update the semantic (ontology) probabilities that describes the likely geometric and other relationships in this world.	**Accuracy of geometric world model update; Correctness and consistency of semantic probabilities**
Experiment	*Performance indicators*
1.5 Autonomous Structure Inspection	Accuracy, repeatability
3.6 Contact state estimation using force/torque sensor	Correctness

Table 5: Experiments and performance indicators related to S&T 1.3

S&T Objective	*Performance Assessment*
S&T 1.4 To diagnose the state of task execution based on status data from the execution layer and the world model, and to maintain the ontology describing the possible effects of action and the current task status.	**Correctness of diagnosis; Correctness of task status**
Experiment	*Performance indicators*
1.3 Fault management	Accuracy, repeatability, valid pose, computer power, TRL

Table 6: Experiments and performance indicators related to S&T 1.4

S&T Objective	*Performance Assessment*
S&T 1.5 With the assistance of the planner, autonomously direct the attention of sonar and video sensors to appropriate places in the work-volume, to provide needed world updates.	**Correctness of sensor attention**
Experiment	*Performance indicators*
1.4 Focus of Attention	active vs passive
1.5 Autonomous Structure Inspection	Accuracy, repeatability
2.1 Horizontal Chain Detection and Following with FLS	Percentage of detected links, accuracy, following success and detection vs chain layout, speed, TRL
2.3 Vertical Chain Detection and Following with FLS and multibeam sonar	Accuracy with MB and FLS, success rate, following speed, TRL
2.7 Horizontal and vertical chain inspection at sea	Percentage of detected links, accuracy, following success and detection vs chain layout, speed, Accuracy with MB and FLS, success rate, following speed, TRL
3.7 Combined long term experiment in water tank	Correctness, accuracy, performance, computer power, TRL

Table 7: Experiments and performance indicators related to S&T 1.5

S&T Objective	*Performance Assessment*
S&T 2.1 Extend hindsight optimisation planning to metric domains	**Evaluation of competence against benchmark probabilistic metric problems**
Experiment	*Performance indicators*
4.6 Plan-Based Policy Learning	Efficiency, TRL

Table 8: Experiments and performance indicators related to S&T 2.1

S&T Objective	*Performance Assessment*
S&T 2.2 Develop plan repair and adaptation techniques, including opportunistic adaptation without sacrificing key commitments	**Performance in context of changing goals and world description**
Experiment	*Performance indicators*
1.1 Planning for Structure Inspection	Plan quality, planner, planning time, TRL,
1.5 Autonomous Structure Inspection	Accuracy, repeatability
3.4 Temporal Planning for Valve Turning Scenario	Plan quality, planner, planning time, TRL
3.7 Combined long term experiment in water tank	Correctness, accuracy, performance, computer power, TRL
4.7 Planning and Persistent Autonomy	Replanning number of times, duration, scaling of planner, lost goals, TRL

Table 9: Experiments and performance indicators related to S&T 2.2

S&T Objective	*Performance Assessment*
S&T 2.3 Support plan-fragment insertion to enable the AUV to take advantage of unexpected opportunities when resource availability allows	**Added-value in terms of goals achieved and efficiency of resource use**
Experiment	*Performance indicators*
2.6 Opportunistic Planning	Potential additional goals, plan quality, planner, planning time, TRL
4.7 Planning and Persistent Autonomy	Replanning number of times, duration, scaling of planner, lost goals, TRL

Table 10: Experiments and performance indicators related to S&T 2.3

S&T Objective	*Performance Assessment*
S&T 2.4 Enable extensions and updates to the planner's world model	**Correctness of the model and extension of the planner functionality**
Experiment	*Performance indicators*
1.1 Planning for Structure Inspection	Plan quality, planner, planning time, TRL,
1.5 Autonomous Structure Inspection	Accuracy, repeatability
3.4 Temporal Planning for Valve Turning Scenario	Plan quality, planner, planning time, TRL
4.7 Planning and Persistent Autonomy	Replanning number of times, duration, scaling of planner, lost goals, TRL

Table 11: Experiments and performance indicators related to S&T 2.4

S&T Objective	*Performance Assessment*
S&T 3.1 Develop imitation learning and reinforcement learning algorithms to learn PHMM representations of skills, including both synthesis and recognition of skills.	**Correct recognition and synthesis of learned skills; Ability to generalize skills with variable parameterization**
Experiment	*Performance indicators*
3.3 Learning by demonstration for valve turning	Similarity, success rate, resiliency, accuracy, task scalability, computer power, TRL
3.5 Reactive behaviour learning for valve turning	Similarity, task scalability, computer power, TRL
3.6 Contact state estimation using force/torque sensor	Correctness
3.7 Combined long term experiment in water tank	Correctness, accuracy, performance, computer power, TRL

Table 12: Experiments and performance indicators related to S&T 3.1

S&T Objective	*Performance Assessment*
S&T 3.2 Develop covariance analysis method for reinforcement learning to achieve robust skill execution in noisy unstructured underwater environment.	**Correct detection of multiple local optima; Correctly incorporating covariance information in policy decision making**
Experiment	*Performance indicators*
4.8 Thruster failure recovery using reinforcement learning	Optimization method and computational cost

Table 13: Experiments and performance indicators related to S&T 3.2

S&T Objective	*Performance Assessment*
S&T 3.3 Develop reinforcement learning with multi-dimensional reward for speeding up the robot skill learning process.	**Achieving significant speed up of the learning process**
Experiment	*Performance indicators*
4.8 Thruster failure recovery using reinforcement learning	Optimization method and computational cost

Table 14: Experiments and performance indicators related to S&T 3.3

S&T Objective	*Performance Assessment*
S&T 4.1 To develop a robust control module to act as an interface between the high-level modules and the hardware of the UVV platform.	**Effectiveness (speed, accuracy) of implementation of high level commands.**
Experiment	*Performance indicators*
2.1 Horizontal Chain Detection and Following with FLS	Percentage of detected links, accuracy, following success and detection vs chain layout, speed, TRL
2.3 Vertical Chain Detection and Following with FLS and multibeam sonar	Accuracy with MB and FLS, success rate, following speed, TRL
2.4 Chain cleaning with water jet	TRL
2.7 Horizontal and vertical chain inspection at sea	Percentage of detected links, accuracy, following success and detection vs chain layout, speed, Accuracy with MB and FLS, success rate, following speed, TRL
3.7 Combined long term experiment in water tank	Correctness, accuracy, performance, computer power, TRL
4.4 A Methodology for Interaction Control:Design of a UVMS Motion Control Scheme	Pose achievement

Table 15: Experiments and performance indicators related to S&T 4.1

S&T Objective	*Performance Assessment*
S&T 4.2 To develop robust UUV motion control methodologies compensating for the disturbances emanating from the environment.	**Target Tracking performance under various levels of disturbances.**
Experiment	*Performance indicators*
1.2 Robust Motion Control of Nessie VI	Error in steady state
1.5 Autonomous Structure Inspection	Accuracy, repeatability
2.5 AUV control with water jet perturbation	Tracking error
4.2 AUV Online and Offline dynamic model identification	Fitting score
4.3 Control of Underactuated Underwater Vehicles	Tracking error
4.4 A Methodology for Interaction Control:Design of a UVMS Motion Control Scheme	Pose achievement

Table 16: Experiments and performance indicators related to S&T 4.2

S&T Objective	*Performance Assessment*
S&T 4.3 To develop interaction control methodologies to implement interaction forces and torques needed to realize a task.	**Accuracy of interaction task implementation for various scenarios**
Experiment	*Performance indicators*
4.4 A Methodology for Interaction Control:Design of a UVMS Motion Control Scheme	Pose achievement

Table 17: Experiments and performance indicators related to S&T 4.3

S&T Objective	*Performance Assessment*
S&T 4.4 To extend the operation envelope of a UUV by developing a sensor based control scheme, enabling it to perform as an almost 360° pitch sensor for inspection of surfaces independently of their orientation	**Maximum hovering angle; Accuracy of positioning under various levels of visibility and target motion**
Experiment	*Performance indicators*
4.5 Servoing Control Methodologies for UUV Hovering around Large Pitch Angles	Pose achievement

Table 18: Experiments and performance indicators related to S&T 4.4