Dexterous Undersea Interventions with Far Distance Onshore Supervision: the DexROV Project

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Abstract: The operation of a ROV requires significant off-shore dedicated manpower to handle and operate the robotic platform. In order to reduce the burden of operations, DexROV proposes to work out more cost effective and time efficient ROV operations, where manned support is in a large extent delocalized onshore (i.e. from a ROV control center), possibly at a large distance from the actual operations, relying on satellite communications. The proposed scheme makes provision for advanced dexterous manipulation capabilities, exploiting human expertise from a remote location when deemed useful. The outcomes of the project will be integrated and evaluated in a series of tests and evaluation campaigns, culminating with a realistic deep sea (1,300 meters) trial. After one year, the project specified the system architecture of the system and carried out preliminary technological trade-offs for the subsystems.

Keywords: ROV, long range teleoperation, communication latencies, force feedback, real time simulation, machine learning, 3D perception, 3D modelling, autonomy, dexterous manipulation

1. INTRODUCTION

DexROV is a EC Horizon 2020 funded project addressing the development of under-sea robotic intervention capabilities, with a focus on (1) far distance teleoperation – involving variable communication latencies to mitigate, and (2) dexterous manipulation capabilities benefiting from context specific human skills and know-how. DexROV intends to develop cost-effective technologies and methods that will enable subsea operations with fewer off-shore personnel while increasing the range, flexibility and complexity of operations that are possible. The consortium consists of 9 European organizations, coordinated by the Belgian company Space Applications Services. Academic partners include the Italian Universities of Genova, Cassino and Salento, the German Jacobs University Bremen, and the Swiss IDIAP research laboratory (affiliated to EPFL). Industrial partners include COMEX (France), GRAAL TECH (Italy) and EJR Quartz (Netherlands).

Section 2 introduces the motivation and challenges of DexROV. Section 3 then presents the DexROV concept and architecture. Section 4 provides more details about the main subsytems and related work done after one year. Section 5 gives further insight into the planned validation and evaluation strategy. Section 6 deals with acknowledgements.

2. CHALLENGES

Performing inspection and maintenance (I&M) tasks in harsh environments and working in remote hazardous locations requires perception, understanding and capability for flexible interaction and responses. Such resourcefulness has been demonstrated both remotely and in situ during the construction and operation of the International Space Station [ESA 2014]. The same goes for a range of demanding subsea operations, where professional divers are often requested to carry out demanding operations requiring dexterity. For instance wet arc welding techniques such as Shielded Metal Arc (SMAW) is such an operation. Commercial diving is however complex and expensive to organize and carry out, while being considered a harsh and risky activity (acute hazards such as decompression sickness, debris impacts, blocked access to surface, entanglements; but also long term consequences correlated to significant compressed air exposure). The majority of today's offshore interventions are in shallow water however even these operations are risky. The following extract from the UK Health & Safety Executive's (HSE) 2011/2012 Offshore Safety Statistics

Bulletin [HSE 2012] records 36 major injuries during the period and two fatalities, one being a fall from height and the other a diving fatality. In 2012/13 the HSE showed that injuries which occurred in the environments of 'Maintenance/Construction' (57) has been the major category in the last 4 years with 1/3rd of all major injuries.

Furthermore, the depth at which divers can work rarely exceeds 100 meters deep.

For these reasons, ROV based operations are usually preferred to diver based operations when technically feasible – i.e. for duties that do not require high dexterity. However today's ROVs have limitations and are expensive to operate from off-shore vessels. They typically require an offshore crew consisting at least of: (1) an intendant, (2) an operator, (3) a navigator and often more staff (e.g. due to work shifts). Furthermore, customer representatives often wish to be physically present offshore in order to advise on, or to observe the course of the operations. Costs associated to the overall offshore logistics are high.

In DexROV we identify one of the major challenges to be the development of novel, advanced capabilities that allow ROV platforms to perform dexterous tasks that, so far can only be achieved by human divers. Such capabilities shall result in reduced intervention preparation time and effort, less risks, and less costs (e.g. offshore divers wages, insurance, transport, accommodation facilities, medical facilities and support, etc.).

Furthermore we identify as a second important challenge the possibility to offer dexterous manipulation capabilities in depth that cannot be reached by commercial divers (i.e. deeper than 150 meters, typically).

DexROV is tackling these two challenges: the long term vision is to enable onshore supervision and control of ROVs equipped with dexterous bi-manipulator capability without requiring divers or an extensive, permanent offshore support crew. The project will research and develop the innovative capabilities needed, integrate them, ensure compatibility with existing standards, and will validate the results in a realistic deepwater offshore trial at sea on a 1,300 m deep application representative mock-up.

3. CONCEPT AND ARCHITECTURE

DexROV setup consists of the following elements (illustrated on Fig. 1):

- On the offshore side, a vessel (with reduced crew) and a medium class ROV ("hybrid ROV", as it is enhanced with advanced autonomous navigation and manipulation capabilities) equipped with a dedicated, modular sensors extension and a purposely developed bi-dexterous manipulation skid. The vessel is equipped with a satellite communication link.
- On the onshore side, a monitoring and control centre, with the required facilities to allow remote human supervision and intervention – in particular, exploiting force feedback exoskeleton technologies to instruct dexterous manipulation actions.

As a main strategy to mitigate communication latencies between the onshore control centre and the offshore deployed system, DexROV will develop a real time simulation environment (Objective 1) that will allow accommodating operators' interactions (and will in particular enable haptic feedback) in real time on the onshore side. The simulated environment will exploit centimetre accuracy 3D models of the environment built online, relying on the perception and modelling capabilities of the ROV (Objective 2). A cognitive engine (relying on state of the art machine learning techniques) will interpret and translate dexterous user movement into manipulation and navigation primitives that the ROV can handle and achieve autonomously (Objective 3) in the real environment - independent of communication latencies. Intuitive and effective user interfaces (Objective 5) will be developed, including a pair of anthropomorphic arm and hand force feedback exoskeletons. The ROV will be

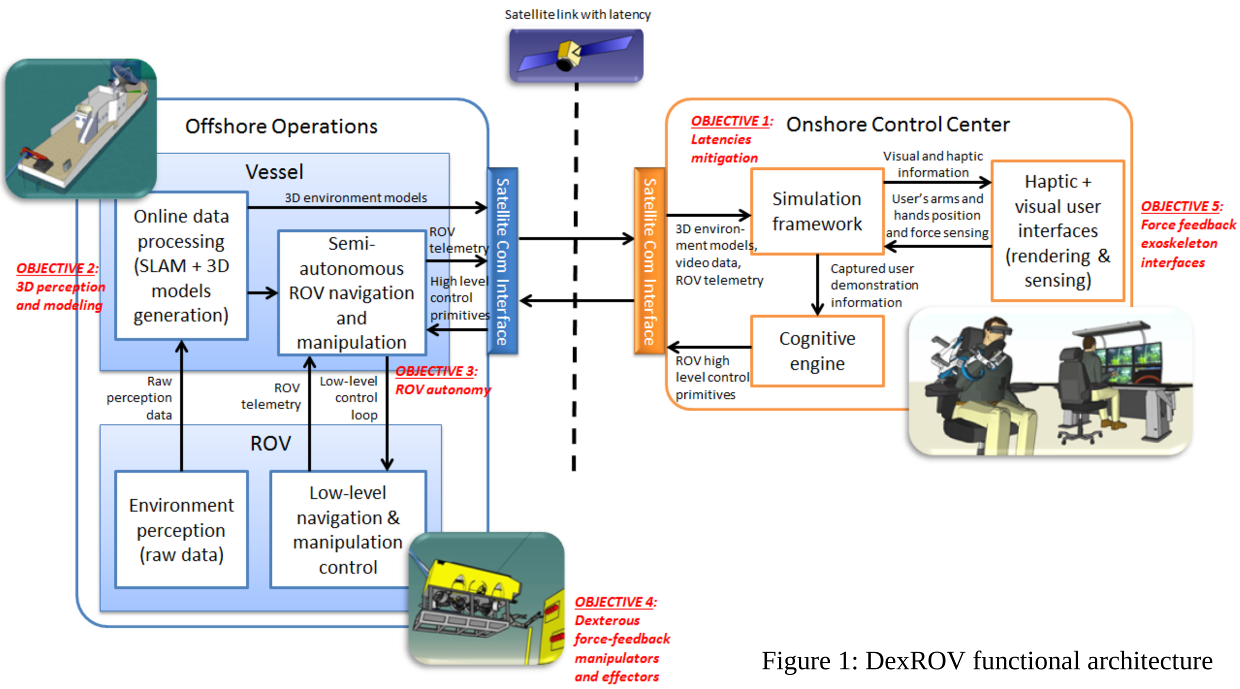

Figure 1: DexROV functional architecture

equipped with a pair of force sensing capable manipulators and dexterous end-effectors (Objective 4) that will be integrated within a modular skid fitting with a range of standard mid-size ROVs.

4. SUBSYSTEMS AND CAPABILITIES

4.1 Underwater perception and mapping

Machine perception is a very challenging topic for underwater applications, and has so far been limited to 2D mosaicking and 2.5D bathymetric mapping. Recently, there is also an increasing interest in underwater 3D mapping and perception. But this work is predominantly concerned with the posterior generation of high-fidelity 3D representations from recorded sensor data after the mission (e.g., [Fairfield 2007], [Sedlazeck 2009], [Saez 2006]). Nevertheless, modern marine applications scenarios addressed in DexROV involve operations in close proximity to complex environments.

The perception approach in DexROV thus contains two major lines of research: a) Online accurate and reliable navigation and mapping to facilitate safe operations relative to subsea installations and other structures, and b) online object detection, recognition, modelling, and tracking to facilitate semi-autonomous manipulation actions relative to them.

Regarding a), very robust and fast 3D registration and tracking techniques such as the ones developed in [Bulow 2013], [Pfingsthorn 2016], are used that are particularly suited for online processing of underwater data [Pfingsthorn 2012]. The robust online capabilities that are being developed in DexROV provide substantial progress beyond the state of the art, which is as mentioned dominated by manual operations, respectively post-mission offline processing of data for modelling complex structures.

Regarding b), novel shape-based object detection techniques [Müller 2014] will be combined with registration and tracking techniques from a) to provide continuously updated object hypotheses and according models to the operator and the autonomous manipulation capabilities of the ROV.

The machine perception in DexROV involves a high amount of online 3D data processing. This starts with the acquisition of underwater 3D data or more precisely of 2.5D range data or short scans. Stereo vision has been identified as the sensing modality of choice because of the high accuracy and update rate. An important contribution will be the online estimation of stereo ranges under adverse conditions (such as marine snow), as well as the development of novel and efficient range uncertainty models taking into account these conditions. This spatial data will in addition be used in novel online robust 3D Simultaneous Localization and Mapping (SLAM) techniques that are being built upon recent methods [Pfingsthorn 2015] to achieve large-scale reliable navigation.

4.2 Autonomous navigation and manipulation

The state of the art technology used in underwater inspection is represented by AUVs (Autonomous Underwater Vehicles) for monitoring applications. In such a case, the vehicle(s) generally travel at constant cruise velocity following pre-planned paths. Some features such as the “mowing the lawn” pattern are currently possible with off-the-shelf products [Stockey 2005]. Some embryonic autonomous modes are also common in ROV and AUV commercial vehicles such as attitude or station keeping also in the presence of ocean current. In the FP7 project ARROWS, semi-autonomous techniques are under development for the specific case of underwater archaeology. Recently, some attempts to achieve on-line path planning based on the information acquired and exchanged with other vehicles have been made, e.g., the project FP7 Co3AUVs [Marino 2013], [Birk 2012]. On the other hand, when a close inspection or low velocities are required, ROV are typically used. Most operations need to be performed by the operator, with existing ROV solutions. This is especially the case in missions requiring manipulation operations: in such cases, the operator's skills and experience are critical factors. As an example, autonomous manipulation has been experimented with using a stabilised (clamped) hybrid ROV and a conventional manipulator in the FP5 ALIVE project, about 10 years ago. However, free dexterous manipulation is very challenging and has only been experimented with recently – for instance the recent EC project FP7 TRIDENT achieved good results in implementing control laws to start automating some hybrid ROV navigation and manipulation operations.

In DexROV, the remote operator will have access to a number of tools to assist him with the navigation of the ROV and the manipulation tasks. Such tools will allow making sure that the focus of the operator is on the top mission goals, i.e. inspection or manipulation operations. The classical example concerns the movement of the end-effector while the tools are taking charge of safety and optimization aspects such as avoiding mechanical joint limits or increasing the manipulability. In DexROV, existing algorithms are being properly tailored and engineered to comply with such requirements and constraint, while new theoretical aspects are being further investigated to handle set-based/inequality control of controlled variables [Antonelli 2014, Malerba 2014, Moe 2016, Simetti 2013].

4.3 Deep water dexterous manipulator and effector

Though a number of high quality (haptic capable) dexterous manipulator arms and effectors exists for ground applications (Kuka LWR, Barrett arm and hand, etc.), bringing similar capabilities in (deep) water remains a major challenge.

Interventions in deep water are routinely performed with hydraulic manipulators mounted on work class ROV, which can easily cope with high pressure environments. Despite some of them arguably exhibit convicting dexterous properties, like the TITAN4 of Schilling Robotics, they are too large devices for the considered observation-class ROV and are not equipped with the desired force sensing capabilities.

Moving from this, in DexROV an innovative electric-driven dexterous arm + effector manipulation solution is currently under analysis, by exploiting previous Graal Tech experiences with underwater manipulators [McGrane 2015], [Ribas 2015], [UMA 2015]. The idea is to design a compact enough system in order to integrate two dexterous manipulators within the skid to be mounted under the Apache ROV, to allow for the execution of bi-manual manipulation tasks.

In this light, one of the main challenges driving the design phase so far has been to find a suitable trade-off between the desired high dexterity and the necessary compactness of the system. The conceptual design of the system has been recently completed [fig. 1] and is constituted by the following components:

- a hand with three fingers (each of them with 2 active degrees of freedom, for flexion and abduction) allowing it to grasp and manipulate a wide range of object shapes [fig. 2].
- a supporting manipulator with 6 degrees of freedom, maximising the work space and allowing the end-effector to be accurately oriented.

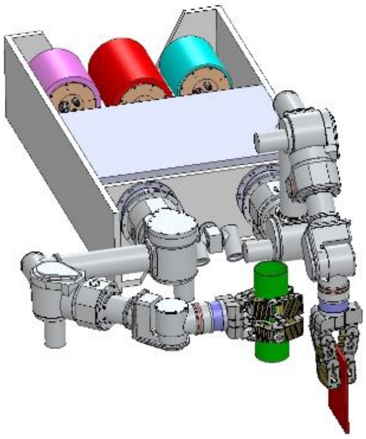

Figure 2: Dual arm dexterous manipulator concept

After the manipulators and end-effectors kinematic structures were defined, the design efforts now focus on two other major challenges: i) coping with the high operative pressure (1,300 meters); ii) integrating a rich sensory system, providing force and position feedback.

Filling the system with oil is a common practice for compensating the mechanical forces exerted on the structure by the water. Then an oil compensator allows to maintain the internal pressure of the oil slightly greater than the ambient pressure, avoiding the possibility of water leakages. However the presence of a high pressure inside the system induces severe mechanical stresses to the internal parts. Particularly critical are the electronic boards, as some components (like the electrolytic capacitors or some oscillators) have gas inclusions and therefore need to be properly shielded by encapsulation in some resin or other protecting material. Furthermore the presence of oil induces some limitations, as not all the components of a mechatronic system are oil-compliant. For example motor brakes of brushless motors do not work properly with oil, as their braking action is based on mechanical friction. Similarly, optical encoders are not compatible with hydraulic. The second challenge consists in the integration of force sensing devices, capable of providing a good enough resolution within a wide range of operative depths. A commercially available underwater 6-axis F/T sensor will be mounted on the wrist. However the more crucial part is constituted by the sensors for the hand, where COTS components do not exist. Different sensing technologies are currently under investigation.

Once a proper solution will be identified, the integration of compact force sensors in the fingers will allow the development of advanced control algorithms relying on force perception and will make the overall DexROV manipulation system a unique, deep water rated underwater dexterous manipulation solution.

4.4 Remote control center and communication latencies mitigation

There are several large-scale ongoing projects to improve the quality of services of current Medium Earth Orbit (MEA) and Low Earth Orbit (LEO) satellites. O3b Networks, Ltd. is for instance one such next generation of network communications service providers. However achieving reliable, affordable, low latency and high bandwidth satellite communication in demanding (offshore...) locations nevertheless remains a long term perspective. The Cobham Sailor 800 3-axis stabilized and tracking Ku band antenna qualified for marine operations was selected as the offshore communication antenna in DexROV. VSAT communication provider Omniaccess has provided a progressive throughput data plan during the course of the project. The upper limit of forward (onshore to offshore) bandwidth is 256Kbps and return (offshore to onshore) bandwidth is 768Kbps.

The software deployed within the onshore control center, offshore ROV control and perception components expose ROS interfaces. A ROS<->DDS proxy (or bridge) binds the two sides for managing data flows with dynamic adjustment of QoS (Quality of Service). Data flows are prioritized based on their order of delivery, liveliness, deadlines and queue lengths. Run time adjustments to the QoS are based on data delivery performance and network connectivity.

Besides satellite communication link management, an essential part of the latency mitigation strategy in DexROV is the cognitive engine. It relies on virtual environments (with physics simulations) and a model based on compact probabilistic movement primitives, to create a telemanipulation system that is robust to nonhomogeneous and low transmission rate, low bandwidth and latency. The user teleoperates the virtual robot and receives haptic feedback from the exoskeleton (arms and hands) in a fluid manner, within the local virtual environment, and without having to concern about the transmission delays. On the onshore site (ROV control centre), the simulation allows the operator to control the arm without disruption, with a limited and controlled number of re-synchronisation steps. On the offshore site, the use of probabilistic models of movement primitives is exploited to locally anticipate which actions and/or regulation feedback policies to adopt until a new command or sensory information is available.

A machine learning framework is applied to model the tasks that the operator performs. This model can then be used to generate new task-adaptive manipulation strategies. On the teleoperator side, the model is used to recognise the tasks that the operator is performing and build a library of teleoperated motion/behavior primitives. On the ROV side, the same model is used to semi-autonomously operate, with robustness to communication latency or inaccuracy of the transmitted signals. This model builds upon a recently developed task-parameterised mixture model, which has proven to be robust in a range of tasks and for various types of dynamic generalization requirements [Calinon 2013, 2014], [Rozo 2013], [Tanwani 2016]. The approach relies on an extension of Gaussian mixture model (GMM) acting in multiple coordinate systems in parallel, which allows the generalization of the learned skills to new situations that were not demonstrated during training. The approach can be used to generate motions according to the task at hand in a semi-autonomous manner, and/or to regulate the input of the operator to suit the current scenario in a shared-control strategy.

On the onshore control centre side, we make provision for the development of dexterous force feedback manipulation capabilities, as part of the DexROV concept. The force feedback exoskeleton arm setup to be used in DexROV will essentially be based on the one initially designed for ESA [Letier 2010] and further improved in the recently completed FP7 ICARUS project. The design of the wearable force feedback exoskeleton hand will be driven by the slave end-effector configuration and capabilities. Compared to most existing hand exoskeleton systems implementing only finger flexion/extension, we will develop a wearable device with 3 fingers having not only flexion/extension, but also abduction (lateral motion) capability, in order to be fully compatible with, and to exploit at its best the new underwater dexterous end-effector to be developed in the project. In order to reduce the overall complexity and bulkiness, we will consider a system based on the association of a soft supporting structure in the shape of a wearable exoskeleton glove and tendon cables to reduce volume and mass of the device around the hand (such as [HyunKi 2011] who proposed a single finger prototype of jointless device with pulling tendons inserted in a glove), enhanced with rigid elements for better stiffness and controllability. Delocalised actuators will be fixed and supported by the lower part of the arm exoskeleton, offering a light and comfortable solution, preserving high quality haptic feedback. The addition of the abduction motion with a softy design approach should lead to a new generation of compact wearable exoskeleton glove enabling dexterous force-feedback manipulation.

5. VALIDATION AND EVALUATION

DexROV outcomes will be progressively integrated, tested, validated and assessed against a set of performance criteria (defined in a preliminary form in the project's work plan for the time being) over the course of the project. A ROS and Gazebo based simulation environment has been setup to support the first stages of the integration and testing of partners outcomes. COMEX will also provide their Janus II vessel, and their APACHE 2500 medium class ROV platform towards the project's needs. The sensor setup and the dexterous manipulation skid are designed so that to fit with this ROV platform, though will be conceived to be compatible with a larger range of platforms.

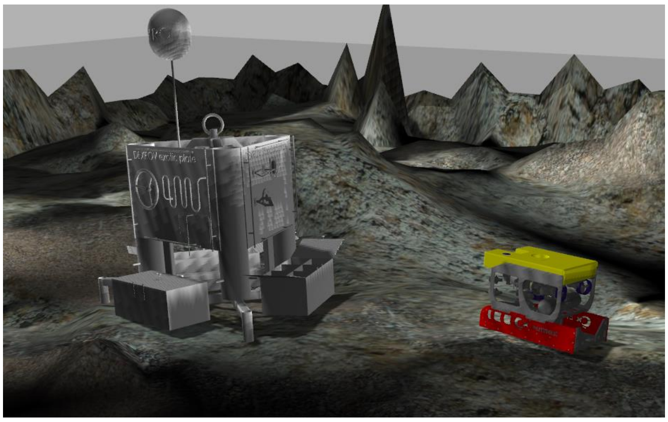

Figure 3: DexROV simulation environment (based on Gazebo)

As a major milestone in the project, a 2 weeks long campaign at sea is planned in the last year of the project, in relevant deep sea condition. A representative deep sea infrastructure mockup has been designed, and will be manufactured to be deployed in the Mediterranean sea at a suitable location (1,300 meters deep). This will serve to demonstrate the capabilities of DexROV.

The first part of the campaign will focus mainly on static inspection related duties, to assess the perception and modelling abilities developed in DexROV, as well as station keeping and low speed navigation support functions. The ROV operation crew (pilot, co-pilot and navigator) will be located on the vessel.

The second part of the evaluation will consist of dynamic inspection (requiring navigation) to assess both the perception and modelling abilities developed in DexROV, the ROV navigation capabilities (and autonomy), and the latencies mitigation paradigms. In this setup, only the co-pilot will stay on the ROV vessel, while the main pilot and the navigator will control and supervise the ROV from the onshore control centre, with communication latencies mitigation. That phase will be based on a representative pipeline structure, either existing (unused) in the vicinity of COMEX facilities, or purposely installed as a representative sample of ~20 meters long.

The third part of the evaluation will focus on the dexterous manipulation duties with the facility mock-up at sea. This will serve to assess the overall DexROV capabilities, with a focus on the force feedback control interfaces usability evaluation, and on the performances of the dexterous manipulation setup of the ROV (arm and end-effector subsystem). As for the second part, only the co-pilot will be located offshore, while the pilot and navigator will control the operations from the onshore control centre (therefore with communication latencies mitigation). The test mockup (Figure 4 above) will include a relevant selection of common ISO interfaces (e.g. various handles types), as well as representative testbeds to test and evaluate the effectiveness of dexterous manipulation tasks performance with wide spread tools designed for human handling, and requiring dexterity. As a baseline, tools such as combination torch, welding stinger, and NDT probing tools are foreseen. Ability to grab such tools with the new dexterous effectors, and to operate them effectively, is part of the validation plan.

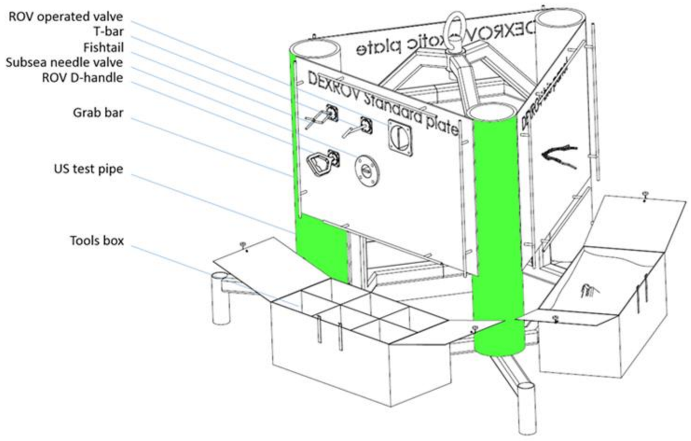

Figure 4: Concept of test mockup for DexROV validation

Performances will be evaluated along the project against a set of key performance indicators, that addresses aspects such as perception and modelling accuracy and time, autonomous capabilities efficacy, effectiveness of latencies mitigation strategies, and overall effectiveness of the DexROV concept versus standard ROV operations and human divers interventions.

6. ACKNOWLEDGMENT

DexROV contributes in the « Blue Growth » long term European strategy to support sustainable growth in the marine and maritime sectors. DexROV is funded through the EC Horizon 2020 programme (Grant #635491).

REFERENCES

[ESA 2014] European Space Agency (ESA) - Building the International Space Station (retrieved on Dec. 2014): www.esa.int/Our_Activities/Human_Spaceflight/International_Space_Station/Building_the_International_Space_Station3

[HSE 2012] UK Health & Safety Executive’s (HSE) 2011/2012 Offshore Safety Statistics Bulletin (retrieved on Dec. 2014): http://www.hse.gov.uk/offshore/statistics.htm

[Fairfield 2007] Fairfield, Nathaniel, Kantor, George A., & Wettergreen, David. 2007. Real-Time SLAM with Octree Evidence Grids for Exploration in Underwater Tunnels. Journal of Field Robotics, 24(1-2), 3–21.

[Sedlazeck 2009] Sedlazeck, Anne, Koeser, Kevin, & Koch:, Reinhard. 2009. 3D Reconstruction Based on Underwater Video from ROV Kiel 6000 Considering Underwater Imaging Conditions. In:IEEE OCEANS Conference ’09.

[Saez 2006] Saez, J.M., Hogue, A., Escolano, F., & Jenkin, M. 2006. Underwater 3D SLAM through entropy minimization. Proceedings of IEEE Int. Conf. of Robotics and Automation,. ICRA 2006, pp. 3562–3567

[Bulow 2013] Heiko Bülow and Andreas Birk. Spectral 6-DOF Registration of Noisy 3D Range Data with Partial Overlap. IEEE Trans. on Pattern Analysis and Machine Intelligence. 35(4), pp. 954-969, IEEE, 2013

[Pfingsthorn 2012] Max Pfingsthorn, Andreas Birk, and Heiko Buelow, Uncertainty Estimation for a 6-DoF Spectral Registration method as basis for Sonar-based Underwater 3D SLAM, International Conference on Robotics and Automation (ICRA), Saint Paul, Minnesota, IEEE Press, 2012.

[Pfingsthorn 2015] Max Pfingsthorn and Andreas Birk, Generalized graph SLAM: Solving local and global ambiguities through multimodal and hyperedge constraints. The International Journal of Robotics Research, 2015, in press, available online.

Pfingsthorn 2016] Max Pfingsthorn, Ravi Rathnam, Tomasz Luczynski, and Andreas Birk, Full 3D Navigation Correction using Low Frequency Visual Tracking with a Stereo Camera. IEEE/MTS OCEANS 2016 Shanghai, China, 2016.

[Müller 2014] Christian A. Müller, Kaustubh Pathak, and Andreas Birk, Object shape categorization in RGBD images using hierarchical graph constellation models based on unsupervisedly learned shape parts described by a set of shape specificity levels. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS), Chicago, IL, 2014, pp. 3053-3060.

[Inmarsat 2009] Inmarsat plc. Fleetbroadband best practices manual, January 2009.

[Calinon 2013] S. Calinon, T. Alizadeh, and D.G. Caldwell, On improving the extrapolation capability of task-parameterized movement models, in Proc. IEEE/RSJ Intl Conf. on Intelligent Robots and Systems (IROS), Tokyo, Japan, 2013, pp. 610-616.

[Calinon 2014] S. Calinon, D. Bruno, and D.G. Caldwell, A task-parameterized probabilistic model with minimal intervention control, in Proc. IEEE Intl Conf. on Robotics and Automation (ICRA), Hong Kong, China, May-June 2014.

[Rozo 2013] L. Rozo, S. Calinon, D. G. Caldwell, P. Jimenez, and C. Torras. Learning collaborative impedance-based robot behaviors. In Proc. AAAI Conference on Artificial Intelligence, pages 1422–1428, Bellevue, Washington, USA, 2013.

[Tanwani 2016] A. K. Tanwani, S. Calinon, Learning Robot Manipulation Tasks with Task-Parameterized Semi-Tied Hidden Semi-Markov Model, IEEE Robotics and Automation Letters, vol. 1 (1), pp. 235-242, 2016.

[Stockey 2005] Stokey, Roger P and others, ``Development of the REMUS 600 autonomous underwater vehicle", OCEANS, 2005. Proceedings of MTS/IEEE, pages 1301—1304, 2005.

[Marino 2013] A. Marino and G. Antonelli, Experimental Results of Coordinated Coverage by Autonomous Underwater Vehicles, Proc. of 2013 IEEE Int. Conference on Robotics and Automation, Karlsruhe, D, pp. 4126--4131, 2013.

[Birk 2012] A. Birk and A. Pascoal and G. Antonelli and A. Caiti and G. Casalino and A. Caffaz, Cooperative Cognitive Control for Autonomous Underwater Vehicles (CO3AUVs): overview and progresses in the 3rd project year, IFAC Workshop on Navigation Guidance and Control of Underwater Vehicles - NGCUV12, Porto

[Malerba 2014] Alessandro Malerba, Giovanni Indiveri, Complementary Control of the Depth of an Underwater Robot, accepetd IFAC World Congress 2014, Cape Town, SA, 2014

[Antonelli 2014] Gianluca Antonelli, "Underwater Robots" , Springer Tracts in Advanced Robotics, Vol. 96 ISBN 978-3-319-02876-7, 3rd ed. 2014.

[Simetti 2013] Enrico Simetti, Giuseppe Casalino, Sandro Torelli, Alessandro Sperinde´, and Alessio Turetta, Floating Underwater Manipulation: Developed Control Methodology and Experimental Validation within the TRIDENT Project, Wiley Journal of Field Robotics, 2013 - Wiley

[HyunKi 2011] In HyunKi, Kyu-Jin Cho, KyuRi Kim, et BumSuk Lee. « Jointless structure and under-actuation mechanism for compact hand exoskeleton ». In 2011 IEEE Int. Conf. on Rehabilitation Robotics (ICORR), 1‑ 6, 2011.

[UMA 2015] http://www.graaltech.it/en/project.php?cid=2&pid=33 by Graaltech (retrieved on March 2015)

[Letier 2010] Letier, P., E. Motard, et J.-P. Verschueren. « EXOSTATION : Haptic exoskeleton based control station ». In 2010 IEEE International Conference on Robotics and Automation (ICRA), 1840‑ 1845, 2010. doi:10.1109/ROBOT.2010.5509423.

[Moe 2016] Moe Signe, Antonelli Gianluca, Teel Andrew R., Pettersen Kristin Ytterstad, Schrimpf Johannes <<Set-based Tasks within the Singularity-robust Multiple Task-priority Inverse Kinematics Framework: General Formulation, Stability Analysis and Experimental Results>>. Frontiers in Robotics and AI, vol. 3, n. 16, 2016.