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Gancet, J., Urbina, D., Letier, P., Ilzkovitz, M., Weiss, P., Gauch, F., ... & Birk, A. (2015, May). DexROV: Enabling effective dexterous ROV operations in presence of communication latency. In OCEANS 2015-Genova (pp. 1-6). IEEE.

The final authenticated version is available online at:
https://doi.org/10.1109/OCEANS-Genova.2015.7271691

You are welcome to cite this work using the following bibliographic information:

BibTeX

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@inproceedings{gancet2015dexrov,
  title={DexROV: Enabling effective dexterous ROV operations in
     presence of communication latency},
  author={J. Gancet and D. Urbina and P. Letier and M. Ilzkovitz and
     P. Weiss and F. Gauch and B. Chemisky and G. Antonelli and G.
     Casalino and G. Indiveri and A. Birk and M. F. Pfingsthorn and S
     . Calinon and A. Turetta and C. Walen and L. Guilpain},
  booktitle={OCEANS 2015-Genova},
  pages={1--6},
  year={2015},
  doi={10.1109/OCEANS-Genova.2015.7271691},
  organization={IEEE}
}
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DexROV: Enabling Effective Dexterous ROV Operations in Presence of Communication Latency

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***Abstract*— Subsea interventions in the oil & gas industry as well as in other domains such as archaeology or geological surveys are demanding and costly activities for which robotic solutions are often deployed in addition or in substitution to human divers – contributing to risks and costs cutting. The operation of ROVs (Remotely Operated Vehicles) nevertheless requires significant off-shore dedicated manpower to handle and operate the robotic platform and the supporting vessel. In order to reduce the footprint of operations, DexROV proposes to implement and evaluate novel operation paradigms with safer, more cost effective and time efficient ROV operations. As a keystone of the proposed approach, manned support will in a large extent be delocalized within an onshore ROV control center, possibly at a large distance from the actual operations, relying on satellite communications. The proposed scheme also makes provision for advanced dexterous manipulation and semi-autonomous capabilities, leveraging human expertise 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 in the Mediterranean sea.**

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

I. INTRODUCTION

DexROV is a newly funded EC Horizon 2020 project addressing the development of new services capabilities under-sea, with a focus on (1) far distance teleoperation of ROV – involving communication latencies to mitigate, (2) advanced dexterous manipulation capabilities benefiting from context specific human skills and know-how – also over long distances and (3) semi-autonomous navigation and manipulation capabilities. DexROV will 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 project is 3.5 years long, starting in March 2015. The consortium consists of 9 European organizations, coordinated by the Belgian company Space Applications Services. Academic partners include the Italian interuniversity center ISME, with the 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 challenges that DexROV tackles. Section 3 further presents the DexROV concept and the proposed approach to address these technical challenges. Section 4 gives further insight into the planned validation and the main evaluation criteria to assess the outcomes.

II. 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 [1]. The same goes for a range of demanding subsea operations, where

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DexROV contributes to 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).

professional divers are often requested to carry out demanding operations requiring dexterity. For instance wet arc welding techniques such as Shielded Metal Arc (SMAW) are typical operations with such requirement. Commercial diving is however complex and expensive to organize and carry out, while being considered a harsh and relatively 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 and, nevertheless even these operations are risky. The UK Health & Safety Executive's (HSE) 2011/2012 Offshore Safety Statistics Bulletin [2][2] 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) and 'Deck Operations' (including air and sea transport) (46) have been the major categories in the last 4 years with 58.9% of all major injuries.

In addition to the risks involved, the depth at which divers can work at is limited to a maximum of 400 to 500 meters.

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 – enabling onshore supervised ROV operations would allow limiting the ROV operation crew to possibly as few as a couple of staffs (essentially for maintenance and deployment/recuperation duties, rather than piloting), and keeping most customer representatives onshore as well - therefore possibly using a smaller and cheaper support vessel.

In DexROV we identify one of the main 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 (according to US stats (2009), about 1 saturation diver out of 1000 loses his life every year), 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 can anyway not be reached by commercial divers (i.e. deeper than 500 meters, typically).

A third challenge is, through advanced perception, modelling, and semi-autonomous navigation and manipulation capabilities, to attempt outperforming conventional ROV in a range of tasks (and environmental conditions) where conventional interventions may be difficult, risky or slowed down – therefore saving time.

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.

III. CONCEPT AND PROPOSED APPROACH

A. DexROV high level concept

DexROV setup consists of the following elements:

- 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.

Fig. 1. below further illustrates DexROV's functional architecture. 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 power 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 primitives into manipulation and navigation actions 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 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. In contrast to e.g. the FP7 PANDORA project [3] that addresses persistent autonomy with AUVs (Autonomous Underwater Vehicles), DexROV promotes effective human support with remotely located operators guidance in complement to the (hybrid) ROV autonomy required in the application context.

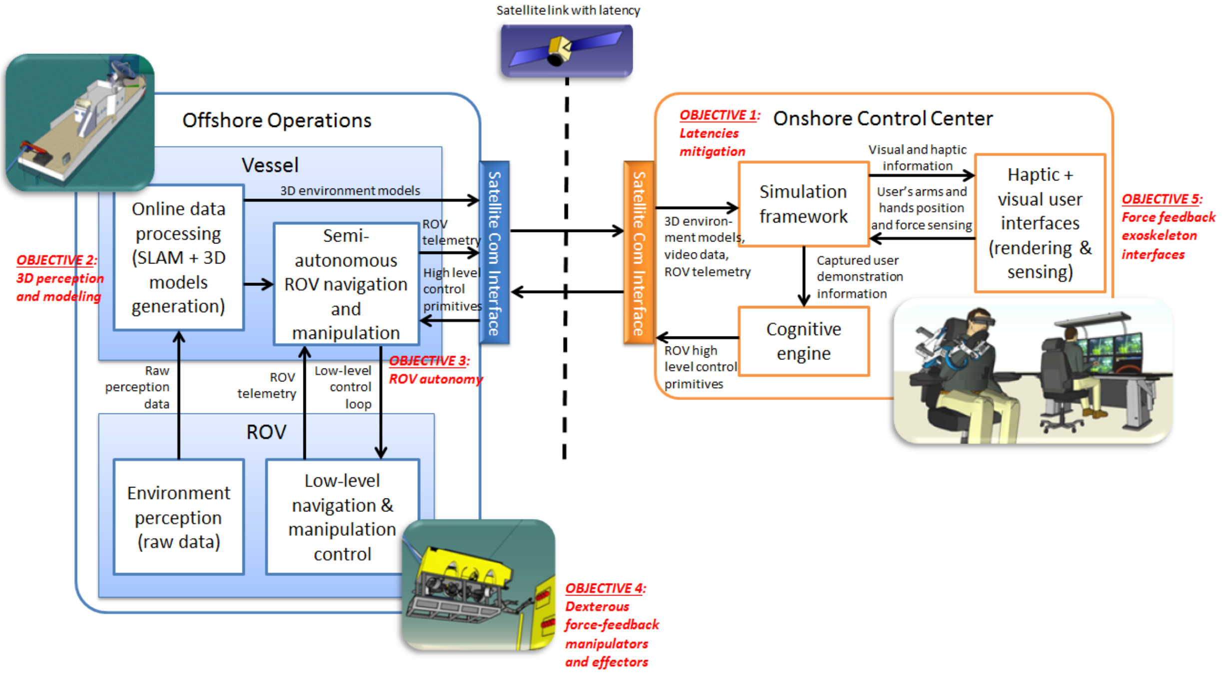

Fig. 1. DexROV functional architecture

B. *Underwater perception and mapping*

Machine perception is a very challenging topic for underwater applications starting with the limitations of available sensors. Visibility is never perfect underwater – even under the best conditions – and is sometimes even non-existent. Sonar sensors have clear deficits with respect to update rates and noise levels compared to “land sensors” like laser range finders. Nevertheless, many marine application scenarios involve complex environments where 2D and even 3D machine perception would be highly desirable or even essential. While there has been significant work on 2D mosaicking and 2.5D bathymetric mapping, 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. [4][5][6]).

The approach in DexROV is to use amongst others very robust and fast 2D and 3D registration techniques such as the ones developed in [8][9][10] that are particularly suited for online processing of underwater data [7][11][12]. The robust online capabilities that will be 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 and operating in complex situations.

The machine perception in DexROV will involve 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. An important contribution will be the online estimation of stereo disparities under adverse conditions (such as marine snow), as well as fitting and outlining of surface patches into noisy underwater scans from a stereo camera. As a challenge, proper uncertainty models will need to be properly determined for the surface representations.

There is finally the issue of Simultaneous Localization and Mapping (SLAM), for which the main challenge in the context of DexROV is to do it in a very fast and robust manner suited for online processing. Building upon existing expertise on robust pose-graph SLAM, adaptations and improvements for higher speed and incremental execution to existing method will be investigated.

C. *Autonomous navigation and manipulation*

The state of the art technology used in underwater monitoring applications is represented by AUVs . 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 [19]. Some basic autonomous facilities are also common in ROV and AUV commercial vehicles such as attitude or station keeping also in the presence of ocean current. Recently, some attempts to achieve on-line path planning based on the information acquired and exchanged with other vehicles have been made in, e.g., the project FP7 Co3AUVs [20][22]. On the other hand, when intervention or a close inspection at low velocities are required, ROV are typically used. Most operations need to be performed by the operator, with existing ROV solutions. The operator is in charge also of compensating the current or be aware of the umbilical deplyment in the 3D underwater environment in order to avoid entanglement. The latter case, to be manully addressed with custom movement, is the source of waste of time. In missions requiring manipulation operations the operator's skills and experience are critical factors since direct control of the arm joints is available or embryonic kind of master/slave architectures. 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.

Within DexROV, the remote operator will have access to more powerful support tools to control the hybrid ROV. A number of tasks will be supported autonomously to help the operator and allow him/her to focus on the main mission goals: inspection and dexterous manipulation. As an example, while the operator needs to move the dexterous arm end-effector, his/her movements might cause one of the joints to reach its mechanical limits. The proposed approach will allow him/her to move the end effectors as desired while, simultaneously, arrange the additional DOFs of the vehicle-manipulator systems to avoid hitting the mechanical limits. The operator, thus, will not have full control of the robotic system but rather a *shared* robot control, in which autonomy will be designed in order to implement a series of safety or latency mitigation tasks, while the operator may better focus on its overall mission task.

Both the autonomous navigation [23] and the autonomous manipulation capabilities [24] will be addressed in DexROV, as well as optimising the hybrid ROV behaviour by efficiently coordinating the two [25].

D. Communication latency mitigation

For many reasons, there is often a discrepancy between what is advertised by satellite communication service providers and the real latency/bandwidth, and in this domain, marine satellite internet solutions are often worse than terrestrial satellite solutions due to additional constraints. For example, in the FleetBroadband Best Practices Manual [13], it is explained that latency in the FleetBroadband network comprises several factors including the physical distances involved (satellite-to-earth propagation delay of 500 ms), the processing delay within the network infrastructure of 250 ms, as well as the size, availability and prioritisation of appropriate time slots of 150-400 ms. They therefore concede that the total latency of the FleetBroadband network is in the range of 900-1150 ms.

There are several large-scale upcoming 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. Achieving highly reliable satellite communication in demanding (offshore...) locations nevertheless remains a rather long term perspective.

The excessive latencies expected with the satellite communication link could easily create bottlenecks that prevent the data stream from filling the network pipe, decreasing the effective bandwidth of the control signal to be transmitted. Thus, the teleoperation data needs to be transmitted in a compact and robust manner, with granularity for the representation of motion/feedback primitives to be easily selected or adapted to the type and range of available latency and bandwidth.

In DexROV we will go beyond standard online imitation schemes by relying 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.

It is proposed to exploit 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 [14][15][16][17][18]. The approach allows a Gaussian mixture model (GMM) to be adapted to different situations that are not part of the training set. Full covariance matrices can be used in the model, which allows the system to encode the local synergies among and in-between the degrees of freedom of the arms and the hands, which is important for dexterous bimanual skills.

E. Deep water dexterous manipulator and effector

Though a number of high quality (haptic capable) dexterous manipulator arms and effectors exist for ground applications (Kuka LWR, Barett arm and hand, etc.), bringing similar capabilities in (deep) water remains a major challenge. For preserving the integrity of a mechatronic system intended to work underwater and exposed to high pressure, specific design criteria and constructive rules have to be followed. Filling the system with oil is a common practice for compensating the mechanical forces exerted on the structure by the water. In addition, if the internal pressure of the oil is maintained (with a compensator) as slightly greater than the ambient pressure, the possibility of water leakages is practically avoided. In DexROV, the following fundamental characteristics are deemed essential in to fulfill the project objectives:

- an anthropomorphic kinematic design of the arm, possibly with redundancy, maximising the work space and allowing the end-effector to be accurately oriented
- a near anthropomorphic kinematic design of the gripper, allowing it to grasp and manipulate a wide range of object shapes
- a rich, reliable and accurate sensory system – accurately providing force feedback and position information

- advanced control electronics and software - allowing to execute commands with high precision and repeatability, at high frequency

To our knowledge, no COTS underwater manipulators (or effectors) meet all these requirements so far. In terms of kinematic design of arms, the ARM-5E from ECA, has only 5 active degrees of freedom (dof) - some existing manipulators arguably exhibit convincing dexterous properties, like the TITAN4 from Schilling Robotics, but it comes as a much larger device than the human arm (and is in practice used with work class ROV for heavy duty interventions). As far as end-effectors are concerned, 2-jaws grippers are the norm, with a single degree of freedom. The main reason is that in the Oil & Gas industry, most underwater structures are standardised to be effectively manipulated and actuated (wherever relevant) with such 2-jaws grippers – this in some extent inhibited the innovative development of more dexterous, deep water graded effectors. A few prototypes of more dexterous underwater end-effectors have been recently developed: e.g. the SeeGrip from DFKI and the hand developed during the FP7 TRIDENT project by the University of Bologna – these are however lab prototypes and not commercially available. They are moreover much larger than human hands, making them unsuitable for e.g. manipulating standard divers tools.

Following this analysis, an innovative electric-driven dexterous arm + effector manipulation solution will be developed in DexROV. A particular effort will be dedicated to designing highly dexterous kinematic structures: as a trade-off the hand will be featured with three fingers (each of them with 2 active degrees of freedom: one in flexion and one in abduction) and the supporting manipulator will come as an anthropomorphic 7 degrees of freedom appliance. The integration of compact and accurate force sensors in the fingers, in the wrist (based on 6-axis force/torque sensors) and in the other joints of the arm 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 (1,300 meters) underwater dexterous manipulation solution. Previous experience with Graaltech's Underwater Modular Arm [27] underwater robotic arm will very valuable for this purpose. Two such arms will be worked out and embedded in a compact modular skid.

F. Force feedback user interfaces

On the onshore control centre side, DexROV makes provisions for the development of dexterous force feedback manipulation capabilities, despite the presence of latencies.

Kraft telerobotics developed an operational force feedback capable underwater (hydraulic) force feedback arms, and desktop force feedback masters that allows bilateral control. This setup however conveys force feedback only through the operators' hand, and cannot naturally match the user's arm (neither provide as much accuracy) as a full arm and hand force feedback exoskeleton setup would allow.

The force feedback exoskeleton arm setup to be used in DexROV will essentially be based on the one initially designed for ESA [28][29] and further improved in the FP7 ICARUS.

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 [26] 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.

IV. 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. COMEX provides their Janus 2 vessel, and their APACHE 2500 medium class ROV platform towards the project's needs. The sensor setup and the dexterous manipulation skid will be developed to fit with this platform, though will be designed to be compatible with a larger range of platforms, as much as possible. 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. An Oil and Gas industry representative, deep sea infrastructure mockup will be worked out and deployed in the Mediterranean sea at a suitable location (1,300 meters deep).

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. Only observers will be located at the onshore control centre. In that phase, the ability to reconstruct (3D map) seafloor natural environment and artificial structures and to register artificial structure's components with respect to a priori models (e.g. structure sub-parts and grasping interfaces) will be tested and evaluated.

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 standard 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). As a baseline, the test mockup 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.

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.

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