Current Robotics Reports (2020) 1:117–122
https://doi.org/10.1007/s43154-020-00012-7

UNDERWATER ROBOTICS (G ANTONELLI, SECTION EDITOR)

Autonomous Underwater Intervention

Enrico Simetti [1,2]

Published online: 24 June 2020

Abstract

Purpose of Review There is a growing interest and literature on autonomous underwater intervention systems. The purpose of this paper is to provide a review of the recent literature on control systems for autonomous or semi-autonomous underwater manipulation activities, classifying the results based on the type of task executed and the testing environment (simulation, pool, or sea).

Recent Findings Amongst underwater intervention tasks, the grasping of objects lying on the seafloor is one of the most studied topics. Several results are given both in pool and sea environments. The perception of such objects might still need further improvements before the system can be considered robust enough. Manipulation of valves while docked has been demonstrated in sea environments. Results on floating valve manipulation or floating inspection through force regulation are still limited to pool environments. Finally, cooperative transportation by multiple agents is still limited to numerical simulation results only.

Summary A review of the state of the art of underwater manipulation is presented. First an introduction is given, recalling the fundamental milestones reached in the past on this topic. Then, recent findings on control systems for (semi-)autonomous intervention are presented, subdivided in grasping, valve manipulation and force regulation tasks and cooperative manipulation. Some unconventional systems are also presented.

Keywords Underwater vehicle manipulator systems · Intervention autonomous underwater vehicles · Underwater inspection · Underwater intervention · Autonomous underwater manipulation

Introduction

Operations at sea are costly and demanding. The typical tasks performed in the offshore industry require the use of remotely operated vehicles (ROVs) deployed from a surface support vessel (SSV) and operated by a crew consisting at least of an intendant, an operator and a navigator, typically working in multiple shifts to operate full-time. As an example, the cost of ROV SSV for performing acoustic inspection of a pipeline can easily reach 50 k€ per day, as a recent survey highlighted [1]. The same operation, performed by two autonomous underwater vehicles (AUVs), operating in tandem, could decrease the costs by up to 85%. Thanks to numerous breakthroughs, AUVs are now often used in a variety of survey and inspection tasks, e.g. in structural inspections [2], marine geology [3], archaeology [4] and plume tracking [5], and are now consistently featured in research programmes of major international oil and gas players such as Chevron [6].

However, while AUV technology has reached a high technology readiness level for the aforementioned applications, there is still a technological gap for applications that require interaction with the environment, e.g. maintenance of submerged oil wells, cabled networks and pipelines. These applications require that the AUV is endowed with one or more manipulators and appropriate tools, giving rise to the so-called underwater vehicle manipulator systems (UVMS).

Studies on (semi-)autonomous intervention date back to the early 1990s, with the works targeting compliant underwater manipulators [7] and coordinated vehicle/arm control for teleoperation [8]. The European Union (EU) funded AMADEUS project [9] went further on, as it demonstrated dual-arm autonomous manipulation in water tank experiments [10], through the use of novel underwater grippers [11]. During the same years, the use of task-priority frameworks

This article is part of the Topical Collection on *Underwater Robotics*

✉ Enrico Simetti
enrico.simetti@unige.it

1 Department of Informatics, Bioengineering, Robotics and Systems Engineering, University of Genoa, Via Opera Pia 13, 16145 Genoa, Italy

2 Interuniversity Research Center on Integrated System for the Marine Environment, Via Opera Pia 13, 16145 Genoa, Italy

for the kinematic control of UVMS started to be proposed [12]. A true milestone was achieved with the SAUVIM project, which focused on free-floating underwater manipulation [13]. The autonomous recovery of an object lying on the seafloor was achieved for the first time, using a combination of sonars, underwater video cameras and ultrasonic motion trackers sonar data as feedback for the manipulation [14].

Recent Findings

Grasping Objects

The pioneering works mentioned in the introduction laid the foundations for the subsequent developments that have seen a rapid increase in the last decade. The work of SAUVIM was inspiring for the proposal of the EU-funded TRIDENT project, where autonomous free-floating manipulation was again studied. The major difference is that TRIDENT proposed the use of a much smaller AUV and developed a novel electrical manipulator [15]. Given the relatively comparable mass and inertia of the TRIDENT vehicle and manipulator, the motion of the manipulator and of the vehicle is not dynamically decoupled, as de facto happened in the SAUVIM project. A task-priority and dynamic programming-based coordinated control for floating manipulation was developed, exploiting all the degrees of freedom of the UVMS. The proposed control architecture was employed for grasping the mock-up of a black box lying on the sea floor while satisfying a set of control objectives, such as maintaining the object in the field of view, avoiding occlusions caused by the manipulator and respecting the joint limits [16]. The TRIDENT project relied on a couple of stereo cameras and a colour-based algorithm to detect the mock-up of a black box to be recovered [17].

Building on the results of the TRIDENT project, the Italian project MARIS explored once again the free-floating manipulation. A series of pool tests campaigns were conducted, showing the importance of proper vehicle-arm coordination [18•]. Indeed, an optimal control of the manipulator can be achieved if the vehicle's actual velocity is measured while still allowing the vehicle to support the arm in a task-priority fashion. Similar findings were later reported in [19], where different control schemes were compared in terms of end-effector stabilization performance. The aforementioned results were presented in a systematized fashion in a recent publication [20], where a uniform task-priority framework including velocity saturations is proposed to allow the UVMS to execute many different actions, ranging from teleoperation of the end-effector in case of a shared control of a ROV to autonomous grasping, to contact force regulation for pipeline inspection. The framework also manages velocity saturation at the different priority levels. However, except for grasping, the results are limited to hydrodynamic simulations. Finally, the MARIS project relied on stereo image processing as feedback for grasping. Detection and pose estimation exploited robust features like colour, shape and dimension, and they were tested both in day and night conditions [21].

Finally, further works on grasping were done in [22], where a laser scanning system was employed to create a 3D point cloud of the object, driving the UVMS floating manipulation operation. As the authors state, this work is in the initial stages of development, and further development to account for the sensor motion while floating is still needed.

Valve-Turning Operations on Panels

The idea of exploiting a task-priority approach has been adopted once more in the EU PANDORA project, where it was used to perform free-floating panel manipulation [23], although the proposed framework deals only with equality objectives and managing the joint limits with an ad hoc solution. The PANDORA project also included tests with a learning by demonstration paradigm, performing multiple free-floating "valve-turning" operations [24], using a position-only control loop. The work done in the PANDORA project was later extended to include motion planning capabilities. The ROS (robot operating system) package "MoveIt!", widely used in terrestrial robots, has been evaluated in the underwater domain by computing reference trajectories for the UVMS in the configuration space to allow valve turning or connector plug operations on a panel [25]. However, the motion planning considered the UVMS as fully actuated, while roll was only passively stable, which could lead the planner to generate unfeasible trajectories. Furthermore, as evidenced by [18•, 19], the degrees of freedom of the manipulator and the vehicle exhibit different performances and require a proper coordination scheme, and this was not taken into account, as the authors themselves underlined. Rather than relying on motion planning, a recent work has integrated multiple obstacles as a set-based control task, showing autonomous free-floating valve manipulation in a cluttered scenario, executing experiments in a pool [26••].

Moving away from purely autonomous systems, the EU DexROV project [27] focused on the remote control, through satellite communications, of a UVMS umbilically connected to a support vessel from a distant onshore control room. The main idea is that the user performs a supervised control of the UVMS, controlling the motion of the sole end-effector in a virtual environment, while a cognitive engine adapts the reference trajectory of the end-effector to the actual situation offshore, using the perception feedback. The control system takes care of safety-related tasks (e.g. mechanical joint limits, avoiding obstacle in the manipulator's workspace), interaction ones (e.g. exerting a required force/torque on a valve) and prerequisite ones (e.g. maintaining the valve within the field of view of the cameras) using a task-priority approach [28].

The experimental results, performed on a mock-up of a real oil and gas panel deployed at 30-m depth off the coast of Marseille, France, showed how the control system can cope with uncertainty in valve pose estimates due to poor scene visibility. Unexpected collision with the panel is in fact handled successfully by the integrated admittance filter, even in the presence of simultaneous activation of a joint limit [29••].

While the above-mentioned works were implemented with research prototypes and with electrical manipulators, experiments at sea have been performed also with commercial hardware, namely, with the hydraulic Schilling Titan 2 manipulator equipped with a Point Grey BlackFly camera mounted on the wrist of the manipulator. With the aid of fiducial markers, a position-based visual serving algorithm has been implemented and tested with the supporting ROV landed on the seafloor, simulating the situation of the ROV being docked to a panel. Experiments in grasping tools and rotating valves were successfully addressed [30•].

Force Regulation Tasks

For a complete development of autonomous UVMS missions, controlling the force exchanged with the environment is a necessary capability of the robot. Endowing robots with such a skill would open the possibility of executing many operations needed on underwater structures, such as non-destructive testing to inspect a pipeline's weld. Due to the great interest that this capability has, it has been investigated since the early works on UVMS. For example, the work [31] integrates an external PID controller to regulate the contact force, generating a desired velocity which is added to the end-effector's desired one. The work was already proposing the use of a task-priority framework, albeit at that time limited to equality tasks. Contact with the environment was properly categorized as constraint tasks in [20, 32], as the velocity along the surface's normal can only give rise to force and not motion. Hence, a task dealing with the contact constraint was introduced at the highest priority level, allowing lower priority tasks to behave optimally even during contact. Furthermore, the same constraint task was exploited to regulate the force of the contact. This idea was applied to the case study of inspection of a pipeline's weld, and the force regulation task was ensuring that the contact was always maintained. A path on the horizontal plane was assumed as input, with no knowledge of the pipeline's radius. As the robot made contact, a task allowed its end-effector to align to the surface's normal and the constraint task regulated the contact force. The rest of the task hierarchy allowed the UVMS to follow the projection of the horizontal path on the surface of the pipeline while satisfying the joint limits and maintaining adequate manipulability levels [20].

A robust interaction controller is presented in [33], supported by simulation and experimental results in a pool environment, where the UVMS is required to slide its end-effector on the surface of a panel. The force measurements along the desired direction (perpendicular to the panel) were acquired by 4 load cells installed within the panel itself. A limitation of the experiments is represented by the desired path, which was limited to a single axis movement (horizontally with respect to the vehicle). A variable sliding mode dynamic controller is presented in [34] for the hybrid position/force operational space control for underwater manipulation. The work proposes a method for estimating the contact force in absence of a wrench sensor. However, the limitation of the work is that the experimental results are done with a fixed-based underwater manipulator and hence do not consider the problems that arise with floating bases. A sliding mode impedance controller was proposed in [35], and it was validated with experiments in a pool environment. A limitation of the experiments carried within that work is that the manipulator consists only of three degrees of freedom.

Finally, an adaptive admittance controller with a feedforward term was developed in [36•], and preliminary experimental trials were executed in a pool environment, simulating the inspection of a pipeline. The path was generated using cylindrical coordinates, although with a far smaller radius than the true structure due to detection errors, mainly in the distance between the robot and the pipe. Nevertheless, the results can be considered one of the most advanced demonstrations of floating contact force regulation.

Cooperative Manipulation

A very challenging and ambitious scenario regards the employment of cooperative UVMS. While experimental results at sea are available for single agent object grasping and docked panel manipulation and in a pool environment for floating valve turning and force regulation, cooperative manipulation results are still limited to simulated environments due the high complexity of the overall scenario.

One of the first works in cooperative underwater manipulation is reported in [37], where a case study of cooperative transportation of an object by two UVMS is considered. A sequence of two task-priority optimizations is performed by each agent. During the first one, the two systems compute their optimal end-effector velocities, as if they were the only one grasping the object. The optimal velocity might differ from the object's desired velocity due to safety tasks (e.g. joint limits or obstacles in the path). These velocities are exchanged, and through a fusion policy which favours the one in higher difficulty (e.g. due to many safety tasks active), it is then put as the highest priority task in the second optimization by both agents. This cooperative strategy has been simulated considering the hydrodynamic models of the systems and considering different types of communication constraints (e.g. latency, limited bandwidth, half-duplex communication).

The addition of a velocity term depending on the interaction wrenches is also considered.

A control strategy for cooperative manipulation is also proposed in [38]. An external object controller loop generates the desired wrenches for the end-effectors of the two UVMS involved in the cooperative transportation. These wrenches are then compared by each UVMS with their respective actual wrenches and used to generate a desired end-effector position, which is then used within the inverse kinematics algorithm.

Finally, a nonlinear model predictive controller based on a load-sharing technique is proposed in [39] to transport cooperatively the object and steer it along of a computed feasible path within the workspace.

Unconventional Systems

The results presented in the previous sections have been achieved employing UVMS of two main classes: either AUVs modified to host a manipulator or conventional ROVs made more autonomous. This section reports a few more unconventional designs.

The first is the one adopted within the EU ROBUST project, in which three commercially available torpedo-shaped AUVs have been mechanically and electronically connected by a triangular shaped frame. The resulting system is akin to a ROV but is actuated by 15 thrusters and hosts an electrical manipulator at its centre. The goal of the ROBUST UVMS is to perform autonomous mission for deep mining sites, and experiments at pool have been so far published in [40], where the task-priority architecture developed in [20] has been coupled with a perception framework to detect and track manganese nodules, allowing the UVMS to precisely land in front of the nodule, performing a 3D scan with a laser-scanning system and finally performing an in situ measurement of its contents.

Some of the activities performed in the offshore industry require handling heavy payloads and interacting strongly with the environment. These requirements are then in direct relation with the vehicle thrusters' capabilities; e.g. heavy payloads would require more thrusters or more powerful ones, increasing size, costs, and design complexity of the system. To this aim, a hybrid cable-thruster-actuated underwater vehicle manipulator system has been proposed, where the UVMS capability is increased, thanks to the actuated winches, inspired by the concept of cable-driven parallel robots [41]. The results are limited to modelling and numerical simulations.

A bioinspired UVMS was recently proposed, which employs fins to mimic how cuttlefish moves with great manoeuvrability and adaptability. The resulting system is a compact lightweight (less than 52 kg) UVMS which has been experimentally validated in a pool environment for grasping tasks [42]. The same authors later integrated a sliding mode controller and tested the system in the pool with a test-bed comprising an underwater door with an object behind it, simulating the opening of a box in an archaeology scenario [43]. Finally, a hybrid thruster fin UVMS has been proposed to gather marine products such as sea cucumbers and sea urchins and tested at sea [44].

Another bioinspired UVMS is the snake-like robot presented in [45], a multibody robotic mechanism consisting of serially connected links, equipped with longitudinal thrusters and tunnel thrusters along the body. To perform manipulation activities, the idea is that one end of the snake attaches itself to a suitable handle or grab bar, while the other end, using the snake body joints, can be moved in order to perform precision tasks such as close up inspection, cleaning, and opening and closing valves. So far, only free motion tests of this robot have been performed and reported in the literature.

Finally, the Ocean One platform [46] is a ROV, whose shape resembles a humanoid, endowed with two 7 DOF arms and three-fingered hands [47••]. A particularity of this robot is that it is torque controlled. The control architecture implements a hierarchical whole-body control strategy at the torque level. The lightweight arms compensate for the slower body, and the overall response is fast and accurate. The pilot controls the hands of the platform through haptic devices, with feedback coming from the wrench sensors at the wrists of the robot. The haptic devices do not only reflect the filtered contact forces but are actively controlled. This allows the pilot to perform guided motions, which simplifies the teleoperation task for the pilot by reducing its dimensionality [48]. The platform has been validated during a cruise in the Mediterranean Sea, recovering a vase from the *La Lune* shipwreck.

Table 1 Classification of the results based on the type of task executed and test environment

Task	Simulation	Pool experiments	Sea experiments
Grasping	[12]	[18•, 22, 20, 42, 43]	[13, 16, 44, 46, 47••, 48]
Floating panel manipulation		[23–25, 26••]	
Docked panel manipulation			[27, 29••, 30•]
Force regulation tasks	[20, 31, 32]	[33–35, 36•]	
Cooperative manipulation	[37–39]		

Conclusions

Underwater manipulation performed by autonomous robots is a field that is receiving an increased interest in the past few years, and exciting new results are appearing. Since the early milestone on autonomous floating manipulation of the SAUVIM project [13], the hardware and computing capabilities of the platforms have seen a tremendous improvement, allowing the implementation of complex control and perception schemes. Despite only few theoretical results on stability and convergence analysis are available [49], task-priority framework are de facto becoming the standard approach for the control of underwater vehicle manipulator systems [20, 28] due to their high number of degrees of freedom.

In summary, Table 1 presents the results classified based on the type of task executed and test environment. From a quick glance at the table, floating interaction with the environment, either through admittance/impedance scheme or force regulation, still represents a challenge for the control system. Cooperation between multiple UVMS is also a key challenge for the future, as no experimentation is available yet. Improvements of the robustness of the perception system and performance of the communications hardware will mostly likely be decisive in solving these control challenges.

Compliance with Ethical Standards

Conflict of Interest The author declares that he has no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

References

Papers of particular interest, published recently, have been highlighted as:
• Of importance
•• Of major importance

1. "The Efficiencies of Low Logistics, Man-portable AUVs for Shallow Water Survey Operations," 2017. [Online]. Available: https://www.subseauk.com/documents/ncs_survey.pdf.
2. Ridao P, Carreras M, Ribas D, Garcia R. Visual inspection of hydroelectric dams using an autonomous underwater vehicle. J Field Robotics. 2010;27:759–78 7.
3. Wynn RB, Huvenne VAI, Bas TPL, Murton BJ, Connelly DP, Bett BJ, et al. Autonomous underwater vehicles (AUVs): their past, present and future contributions to the advancement of marine geoscience. Mar Geol. 2014;352:451–68, 6.
4. Bingham B, Foley B, Singh H, Camilli R, Delaporta K, Eustice R, et al. Robotic tools for deep water archaeology: surveying an ancient shipwreck with an autonomous underwater vehicle. J Field Robotics. 2010;27:702–17, 6.
5. Camilli R, Reddy CM, Yoerger DR, Van Mooy BAS, Jakuba MV, Kinsey JC, et al. Tracking hydrocarbon plume transport and biodegradation at deepwater horizon. *Science*. 2010;330:201–4, 10.
6. Gilmour B, Niccum G, O'Donnell T. Field resident AUV systems – Chevron's long-term goal for AUV development. In: 2012 IEEE/OES autonomous underwater vehicles (AUV); 2012.
7. Yoerger DR, Schempf H, DiPietro DM. Design and performance evaluation of an actively compliant underwater manipulator for full-ocean depth. J Robot Syst. 1991;8:371–92.
8. Schempf H, Yoerger D. Coordinated vehicle/manipulator design and control issues for underwater telemanipulation. In: *IFAC Control Applications in Marine Systems (CAMS 92)*: Genova; 1992.
9. Lane DM, Davies JBC, Casalino G, Bartolini G, Cannata G, Veruggio G, et al. AMADEUS: advanced manipulation for deep underwater sampling. IEEE Robotics Autom Mag. 1997;4:34–45.
10. Casalino G, Angeletti D, Bozzo T, Marani G. Dexterous underwater object manipulation via multi-robot cooperating systems. In: IEEE international conference on robotics and automation (ICRA); 2001.
11. Angeletti D, Cannata G, Casalino G. The control architecture of the AMADEUS gripper. Int J Syst Sci. 1998;29:485–96.
12. Antonelli G, Chiaverini S. Task-priority redundancy resolution for underwater vehicle-manipulator systems. In: Proceedings. 1998 IEEE international conference on robotics and automation (cat. No. 98CH36146); 1998.
13. Marani G, Choi SK, Yuh J. Underwater autonomous manipulation for intervention missions AUVs. Ocean Eng. 2008;36:15–23.
14. Marani G, Choi SK. Underwater target localization. IEEE Robotics Autom Mag. 2010;17:64–70.
15. Ribas D, Ridao P, Turetta A, Melchiorri C, Palli G, Fernandez JJ, et al. I-AUV mechatronics integration for the TRIDENT FP7 project. IEEE ASME Trans Mechatron. 2015;20:2583–92.
16. Simetti E, Casalino G, Torelli S, Sperindé A, Turetta A. Floating underwater manipulation: developed control methodology and experimental validation within the TRIDENT Project. J Field Robotics. 2014;31:364–85, 5.
17. Bonin-Font F, Oliver G, Wirth S, Massot M, Negre PL, Beltran J-P. Visual sensing for autonomous underwater exploration and intervention tasks. Ocean Eng. 2015;93:25–44.
18.• Simetti E, Wanderlingh F, Torelli S, Bibuli M, Odetti A, Bruzzone G, et al. Autonomous Underwater Intervention: Experimental Results of the MARIS Project. IEEE J Ocean Eng. 2018;43:620–39 **This works presents a task priority control architecture for underwater floating manipulation, encompassing a manipulator-vehicle coordination scheme, supported by experimental results from several pool trial campaigns.**
19. Haugaløkken BOA, Jørgensen EK, Schjølberg I. Experimental validation of end-effector stabilization for underwater vehicle-manipulator systems in subsea operations. Robot Auton Syst. 2018;109:1–12.
20. Simetti E, Casalino G, Wanderlingh F, Aicardi M. Task priority control of underwater intervention systems: theory and applications. Ocean Eng. 2018;164:40–54.
21. Lodi Rizzini D, Kallasi F, Aleotti J, Oleari F, Caselli S. Integration of a stereo vision system into an autonomous underwater vehicle for pipe manipulation tasks. Comput Electr Eng (CAEE). 2017;58:560–71, 2.
22. Palomer A, Ridao P, Youakim D, Ribas D, Forest J, Petillot Y. 3D laser scanner for underwater manipulation. Sensors. 2018;18:1086.
23. Cieslak P, Ridao P, Giergiel M. Autonomous underwater panel operation by GIRONA500 UVMS: a practical approach to autonomous underwater manipulation. In: IEEE international conference on robotics and automation (ICRA); 2015.

24. Palomeras N, Carrera A, Hurtós N, Karras GC, Bechlioulis CP, Cashmore M, et al. Toward persistent autonomous intervention in a subsea panel. Auton Robot. 2016;40:1279–306.
25. Youakim D, Ridao P, Palomeras N, Spadafora F, Ribas D, Muzzupappa M. Autonomous underwater free-floating manipulation using MoveIt! IEEE Robotics Autom Mag. 2017;24:41–51.
26.•• Cieślak P, Simoni R, Rodríguez PR, Youakim D. Practical formulation of obstacle avoidance in the Task-Priority framework for use in robotic inspection and intervention scenarios. Rob Auton Syst. 2020;124. https://doi.org/10.1016/j.robot.2019.103396. **This work shows experimental results from pool trials in executing floating valve manipulation in an environment cluttered with obstacles.**
27. Birk A, Doernbach T, Mueller C, Luczynski T, Chavez AG, Koehntopp D, et al. Dexterous underwater manipulation from onshore locations: streamlining efficiencies for remotely operated underwater vehicles. IEEE Robotics Autom Mag. 2018;25:24–33, 12.
28. Moe S, Antonelli G, Teel AR, Pettersen KY, Schrimpf J. Set-based tasks within the singularity-robust multiple task-priority inverse kinematics framework: general formulation, stability analysis, and experimental results. Front Robot AI. 2016;3:16.
29.•• Di Lillo P, Simetti E, Wanderlingh F, Casalino G, Antonelli G. Underwater intervention with remote supervision via satellite communication: developed control architecture and experimental results within the DexROV project. IEEE Trans Control Syst Technol. 2020:1–16. https://doi.org/10.1109/TCST.2020.2971440. **This work shows experimental results performed at sea, while docked to a mock-up of a real oil & gas panel, of valve manipulation, including an admittance control to manage the interaction.**
30.• Sivčev S, Rossi M, Coleman J, Dooly G, Omerdić E, Toal D. Fully automatic visual servoing control for work-class marine intervention ROVs. Control Engineering Practice. 2018;74:153–67 **This work shows the implementation of visual servoing technique on state of the art work-class ROV hardware.**
31. Antonelli G, Chiaverini S, Sarkar N. External force control for underwater vehicle-manipulator systems. IEEE Trans Robot Autom. 2001;17:931–8.
32. Casalino G, Simetti E, Wanderlingh F. Robotized underwater interventions. In: Fossen TI, Pettersen KY, Nijmeijer H, editors. Sensing and control for autonomous vehicles: applications to land, water and air vehicles. Cham: Springer International Publishing; 2017. p. 365–86.
33. Heshmati-Alamdari S, Bechlioulis CP, Karras GC, Nikou A, Dimarogonas DV, Kyriakopoulos KJ. A robust interaction control approach for underwater vehicle manipulator systems. Annu Rev Control. 2018;46:315–25.
34. Barbalata C, Dunnigan MW, Petillot Y. Position/force operational space control for underwater manipulation. Robot Auton Syst. 2018;100:150–9.
35. Dai P, Lu W, Le K, Liu D. Sliding mode impedance control for contact intervention of an I-AUV: simulation and experimental validation. Ocean Eng. 2020;196:106855.
36.• Cieslak P, Ridao P. Adaptive admittance control in task-priority framework for contact force control in autonomous underwater floating manipulation. In: *IEEE/RSJ International Conference on Intelligent Robots and Systems*; 2018. **This work shows the first experimental results from pool trials on force contact regulation from a floating vehicle simulating the inspection of a pipeline's weld.**
37. Simetti E, Casalino G. Manipulation and transportation with cooperative underwater vehicle manipulator systems. IEEE J Ocean Eng. 2017;42:782–99.
38. Cataldi E, Chiaverini S, Antonelli G. Cooperative object transportation by two underwater vehicle-manipulator systems. In: 2018 26th Mediterranean conference on control and automation (MED); 2018.
39. Heshmati-Alamdari S, Karras GC, Kyriakopoulos KJ. A distributed predictive control approach for cooperative manipulation of multiple underwater vehicle manipulator systems. In: 2019 international conference on robotics and automation (ICRA); 2019.
40. Sartore C, Campos R, Quintana J, Simetti E, Garcia R, Casalino G. Control and perception framework for deep sea mining exploration. In: IROS 2019; 2019.
41. El-Ghazaly G, Gouttefarde M, Creuze V. Hybrid cable-thruster actuated underwater vehicle-manipulator systems: a study on force capabilities. In: 2015 IEEE/RSJ international conference on intelligent robots and systems (IROS); 2015.
42. Tang C, Wang Y, Wang S, Wang R, Tan M. Floating autonomous manipulation of the underwater biomimetic vehicle-manipulator system: methodology and verification. IEEE Trans Ind Electron. 2017;65:4861–70.
43. Cai M, Wang S, Wang Y, Wang R, Tan M. Coordinated control of underwater biomimetic vehicle-manipulator system for free floating autonomous manipulation. IEEE Trans Syst Man Cybern Syst. 2019. https://doi.org/10.1109/TSMC.2019.2944637.
44. Cai M, Wang Y, Wang S, Wang R, Ren Y, Tan M. Grasping marine products with hybrid-driven underwater vehicle-manipulator system. IEEE Trans Autom Sci Eng. 2020. https://doi.org/10.1109/TASE.2019.2957782.
45. Sverdrup-Thygeson J, Kelasidi E, Pettersen KY, Gravdahl JT. The underwater swimming manipulator—a bioinspired solution for subsea operations. IEEE J Ocean Eng. 2017;43:402–17.
46. Khatib O, Yeh X, Brantner G, Soe B, Kim B, Ganguly S, et al. Ocean One: a robotic avatar for oceanic discovery. IEEE Robotics Autom Mag. 2016;23:20–9, 12.
47.•• Stuart H, Wang S, Khatib O, Cutkosky MR. The Ocean One hands: an adaptive design for robust marine manipulation. Int J Robotics Res. 2017;36:150–66 **This work presents an innovative mechatronic design of compliant, tendon-driven robotic hands for the manipulation of irregularly shaped objects.**
48. Brantner G, Khatib O. Controlling Ocean One. In: Field and Service Robotics, Cham; 2018.
49. Antonelli G. Stability analysis for prioritized closed-loop inverse kinematic algorithms for redundant robotic systems. IEEE Trans Robot. 2009;25:985–94.