Remotely Operated Vehicle Taxonomy and Emerging Methods of Inspection, Maintenance, and Repair Operations: An Overview and Outlook

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Remotely operated vehicle (ROV)-based inspection, maintenance, and repairs (IMR) services are costly because operations are traditionally executed by a hired subsea contractor, who then hires a specialized vessel with an entire crew from the vessel owner or the shipping company. Even though this is an established method considered relatively reliable in comparison to human divers, there is a growing need for more versatile, efficient, and economical IMR methods. Innovations that require no or less use of support vessels are mitigating this challenge. The current ROV classifications do not adapt to these innovations. Hence, the lack of a widely accepted ROV classification. Thus, this paper reviews ROV classifications and proposes a classification that poses no hindrance to innovation and conforms to modern developments. The paper then illustrates and reviews the emerging methods of conducting IMR operations by putting together in a concise, yet resourceful manner the ROV technologies and their various configurations to provide a basic meaningful understanding to the audience. This paper also provides a summary of the comparison of the methods and some of their challenges. [DOI: 10.1115/1.4055476]

Keyword: subsea technology

1 Introduction

Remotely operated vehicles (ROVs) are underwater robots tethered or controlled from a surface ship, and they range in complexity and come in many different sizes and capabilities. A wide range of industries use ROVs for various purposes; however, the oil and gas industry has been the main driver of ROV innovations where the industry utilizes ROVs frequently to carry out inspection, maintenance, and repairs (IMR) of offshore structures.

Inspection, maintenance, and repairs is a term used for subsea intervention operations and its objective is to facilitate safe and cost-efficient intervention on subsea installations to maintain a sustainable operation of offshore assets. IMR operations are traditionally performed from vessels. The daily hire rate of these vessels goes into hundreds of thousands of dollars, which increases the overall cost of offshore oil and gas production [1]. Despite this high cost of production, huge revenues were produced, but in early 2014 when there was a drop in crude oil price [2], very low revenues were produced and the first reaction to this by the oil companies was the dismissal of employees and suspension or termination of projects [3]. Since then, oil companies and operators have realized the need for innovation to cut costs for a more profitable business. This led to a series of technological innovations in the methods of conducting IMR operations.

We present an overview of these methods recently proposed with the aim of addressing the cost problems associated with traditional IMR operations. The objective is to investigate these emerging solutions based on the available literature gathered from databases such as Scopus, OnePetro, and Google scholar, then highlight the benefits and drawbacks of each method and offer possible new directions for future research. Consequently, these innovations in ROVs present a challenge to how ROVs are currently classified. Hence, this article attempts to address this challenge and proposes a taxonomy that fits modern developments.

In Sec. 2, a brief background summary of ROV modes of operation is discussed, and in Secs. 3 and 4 we explain autonomous remote operated vehicles (AROVs) and hybrid remotely operated vehicles (HROVs). Section 5 discusses the ROV classification. Section 6 provides an overview of the traditional IMR processes, and Sec. 7 discusses the emerging methods for less costly IMR operations. Lastly, these methods are evaluated, analyzed, and compared in Sec. 8. The discussion and conclusion in Sec. 9 end the paper.

2 Remotely Operated Vehicle Modes of Operation

Remotely operated vehicles are controlled from onboard control rooms on the support vessel or control stations onshore. Depending on the size and capacity of the ROV, the control station can be a simple joystick control and a video display or a large remote control room containing multiple equipment and personnel [4]. ROVs can be controlled via a tether–power cable and a communication cable or wireless remote control, however, most wireless remote control have been via tethers thus far. All efforts made to implement high-frequency wireless communication in water have proven futile. Hence, the means of physical communication

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medium has been the only choice currently. Nevertheless, the forms of communication may come as hard-wire communication, acoustic communication, optical communication, or radio frequency communication [4]. For example, Campagnaro et al. [5] demonstrated that ROVs could be operated wirelessly up to a range of a few tens of meters.

To understand ROV classification, one must first take into account the different modes of operation. ROVs can operate in three modes: teleoperation, semi-autonomous, and fully autonomous. The following provides a brief background of these different modes of operation.

- Teleoperation mode (human operated): Most ROVs are teleoperated; teleoperation is when the operator is in full control of the vehicle, guiding it through the received camera footage. It could be defined as extending one's abilities to a remote environment. This is achieved by the cooperation of humans and robots as they both excel at different abilities. A teleoperation system enables the human operator to remotely explore and manipulate objects. It usually simplifies the interaction between the human and the robot to a level that allows the completion of tasks that neither the human nor the robot could perform alone. The teleoperation system consists of three parts: a master device (a haptic interface) that the human operator holds and manipulates a slave device that manipulates objects based on the commands from the master device, and a controller that couples master and slave devices by transmitting movements and forces between the two devices [6].
- Semi-autonomous mode: Semi-autonomous is a mixture of autonomy and human interaction. The vehicle is equipped with situation awareness (SA) and the capability of path planning. It operates under a human expert's oversight, and the operator can intervene when the vehicle is unable to perform contingency management, path re-planning, or task re-scheduling. In a given simplistic scenario, the unmanned underwater vehicles (UUVs) navigation system indicates the intermediate waypoints, and it is capable of recognizing the situation, path planning between points, autonomous departure/return, and collision avoidance. However, the operator re-plans the mission scenario and decides how to re-arrange the order of visits to the waypoints to compensate for the lost time [7].
- Fully autonomous mode: In this mode, the vehicle can locate its position on a map and generate its trajectory to the assigned waypoints. The system receives a prior knowledge of environmental information including the candidate sequence of waypoints. The vehicle is capable of independent operation as it is equipped with high-level SA, real-time path planning, the ability of contingency management, and task scheduling [7].

Autonomy has several levels, Veres et al. [8] considered a simple three level of autonomy, which was the aforementioned modes briefly discussed, and they serve as the general known autonomy levels. While other authors, like Sheridan and Verplank [9], introduced a scale metric known as Sheridan's scale with 10 levels of autonomy, and others [10] also introduced a new classification/taxonomy, which contains nine levels of autonomy. However, these taxonomies imply that there are discrete levels of intelligence for autonomous systems, and that classes of vehicle systems can be designed to operate at a specific level.

These taxonomies are misleading both from a cognitive science perspective and from observations of actual practice [7]. This problem has extended to the classification of UUV as a whole, causing serious ambiguities. Autonomy and the absence of a tether are the main elements used to differentiate ROVs and autonomous underwater vehicles (AUVs). In the following sections, we will discuss more in detail AUVs and HROVs, and demonstrate how differentiating AUVs from ROVs in this rapidly advancing technology is futile.

3 Autonomous Underwater Vehicles

Autonomous underwater vehicles belong to the group of UUVs along with ROVs. They are considered an independent group because of their autonomous capability and the absence of a tether. Nevertheless, in reality, AUVs are not self-governing. This certainly presents ambiguity on whether they are ROVs or AUVs. Another complication is the misapprehension of the terms automatic and autonomous. There is a considerable difference between these two terms. In automatic systems, the vehicle precisely executes the pre-programed commands without any functionality for choosing or making decisions, while autonomous systems are capable of recognizing various circumstances and making a decision respectively to reconfigure diverse situations. An automatic system cannot place its actions into the context of its environment and decide between different options. An AUV can constantly adapt to a continuously changing environment, independent of human involvement. High levels of autonomy in underwater vehicles still rely on human interventions in complex situations, thus making them not fully autonomous. To make a vehicle genuinely autonomous, more advanced SA is needed [7]. For these reasons, current AUVs are not self-governing or truly autonomous but can be seen as a variant of an ROV with some level of autonomy. When it comes to tethers as criteria for distinguishing between ROVs and AUVs, with technological improvements in underwater communication, the presence or absence of a tether will no longer matter because ROVs will also be operated via a wireless medium. New vehicles termed hybrid ROVs are emerging, which might finally put an end to the dilemma.

4 Hybrid Remotely Operated Vehicle

Hybrid remotely operated vehicles are vehicles that can be classified as neither ROVs nor AUVs because they have both the capabilities of performing the functions of both AUVs and ROVs. Operations have already been carried out using this vehicle in both ROV and AUV modes, albeit, using support vessels of opportunity [11]. The idea of an HROV began with the SWIMMER concept, which was proven in 2001 and it became technically mature for industrialization in 2006 [12]. The SWIMMER vehicle was attached to an AUV to transport it to the site and it was attached to a Subsea Docking Station (SDS), which supplies power, communication, and shelter to the vehicle [12]. The developed SWIMMER vehicle was composed of two separate detachable bodies unlike the hybrids of today that are single-body vehicles. The HROVs of today also have an SDS situated near the subsea production system (SPS).

Over the past years, there have been several projects on HROV; in 2015, Aquabotix released an HROV which they called "hybrid autonomous remote vehicle" for shallow water tasks, and the vehicle could operate fully autonomously or as a tethered ROV. The system was made for survey and inspection, supporting pre-engineering, construction support, and life-of-field condition monitoring [13]. Woods Hole Oceanographic Institute (WHOI) also developed an ROV called Nereus, which can function as an autonomous vehicle [14]. In May 2018, Houston Mechatronics Inc. introduced a state-of-the-art HROV, which they called the Aquanaut robot.

Currently, the difference between ROVs and AUVs is minor, the gap is rapidly closing, and it is not important whether a vessel is called ROV, autonomous remote vehicle, or AUV. What matters is that they are subsea vehicles and what matters today are interfaces. AUVs are not sufficient for IMR because while achieving autonomy is good, there are more complex works beyond autonomous vehicles, and there will be a requirement for real-time command and control that will necessitate the use of ROV; hence, the concept of a hybrid ROV can be operated semi-autonomously [13]. Semi-autonomy allows more robust integrity through having a "person in the loop" to intervene when necessary, and this has

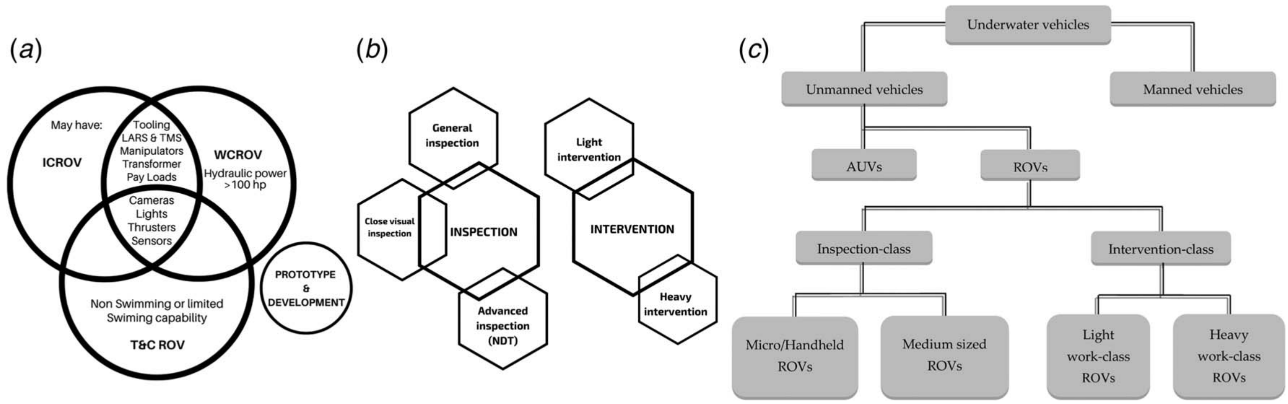

Fig. 1 (a) Shared and non-shared ROV components, (b) capabilities that determine the classification, and (c) underwater vehicle outline [20]

been demonstrated by the Horizon DexROV project that was funded by the European Commission [15,16].

Saab underwater systems[1] also have the concepts of operation and design of an HROV offshore system that can be operated in AUV and ROV modes. The vehicle transits to the location in an autonomous mode and can perform pre-programed inspection and survey tasks, along with other tasks performed manually through the use of tether or low-frequency acoustics [17]. Clean-sea-HROV developed by Eni and Tecnomaye also operates both in AUV and ROV modes without the need for tether management system (TMS), and a lightship could be used to transport it to the site, resulting in significant cost reduction [11]. HROV can also be in the form of a micro-ROV which is a small handheld ROV, such as that developed in Ref. [16]. The new era of technological breakthroughs is freeing ROVs from the need for the constant presence of a support vessel during operations and transforming the way operators work [18]. One can confidently say that the next generation ROVs will operate without the constant need for support vessels.

5 Remotely Operated Vehicle Classification

It is still problematic to classify ROVs and UUVs in general even for the professionals in the field. This is due to the wide range of solutions available and divergent approaches to the classification criteria, hence the lack of a widely accepted standard for ROV classification. New technologies and novel concepts often disrupt the classification. However, generally, classifications look at a group of devices with similar technical characteristics or functionalities, mode of operation and purpose. According to Jakus and Olejnik [19], there are mainly four identifiable approaches or schools of thought to ROVs and/or UUV taxonomy, and the four approaches are as follows:

- *Remotely operated vehicles should not be classified*: This approach holds the belief that ROV classification should entirely be abandoned because a new generation can be launched at any time, perhaps a vehicle that does not fit into the existing classification system. Hence, it is pointless to try to classify the vehicles.
- *Remotely operated vehicles should be classified but needs a frequent update*: This approach holds the belief that at the time when a new solution appears that does not fit within the adopted classification, a new class of devices is created. This school of thought believes that this enhances the ROV taxonomy. It is based on the specification of the tasks performed and the functionalities of particular devices.
- *Remotely operated vehicles should be classified based on weight*: This approach proposes that vehicles can be classified based on a single criterion, weight.
- *Remotely operated vehicles should be classified based on purpose*: This fourth approach is mainly purpose-based. It can be referred to as an open approach. It allows for quite a substantial flexibility in classifying these vehicles in terms of their objectives and the potential interests of the classifier. In the case of manufacturers, on their websites, one can find a classification of vehicles based on mass and the power of the thrusters. The International Maritime Contractors Association (IMCA), which is one of the main organizations and associations issuing norms and standards in the oil and gas industry, also follows this approach for classification.

The fourth approach utilizes the various ROV tasks to classify the vehicles (see Fig. 1(*b*)). For example, it can be seen from the classification given by Capocci et al. [20] in Fig. 1(*c*) that provided a basic classification based on the ROV tasks in Fig. 1(*b*). The approach does not provide a reliable classification because the lines of demarcations between vehicle classes evolved as ROV technology matured. Starting with the drive-force of the prime mover, which is either hydraulic or electric [4] but today, they are also classified based on weight, depth rating, and horsepower as shown in Fig. 2(*a*), capabilities, mode of operation and state of technology as can be seen in IMCA's first classification. These parameters in turn determine the class of the vehicle based on its purpose or task, see Fig. 1(*b*).

Here, we will examine the old IMCA classification; the classification in Ref. [20] and the classification in Ref. [4]; and then we will condense the classifications by integrating the three to better stratify the vehicle systems to fit modern developments. The IMCA's Remote Systems & ROV Division focuses on all aspects of equipment, personnel, and operations relating to robotic intervention in deepwater. They have earlier classified ROVs into five groups: (1) class I—observation ROVs; (2) class II—observation ROVs with payload option; (3) class III—work-class ROVs; (4) class IV—towed and crawling (T&C) vehicles; and (5) class V—prototype and development. This list was updated and published on the IMCA site in 2016.[2] The guidelines now include an expanded list of ROV classifications based upon the increased diversification of tasks performed by ROV systems. This new classification includes an expanded form of ROV, which has a more clear classification and definition based on the continuous diversification of global ROV system development.

The revised classifications are as follows:

(1) Class I—pure observation ROVs.
(2) Class IIA—observation class vehicles with a payload option.

[1] https://www.saab.com/products/security/underwater-systems

[2] https://www.imca-int.com/imca-publishes-revision-to-safe-and-efficient-rov-operations-guidance/

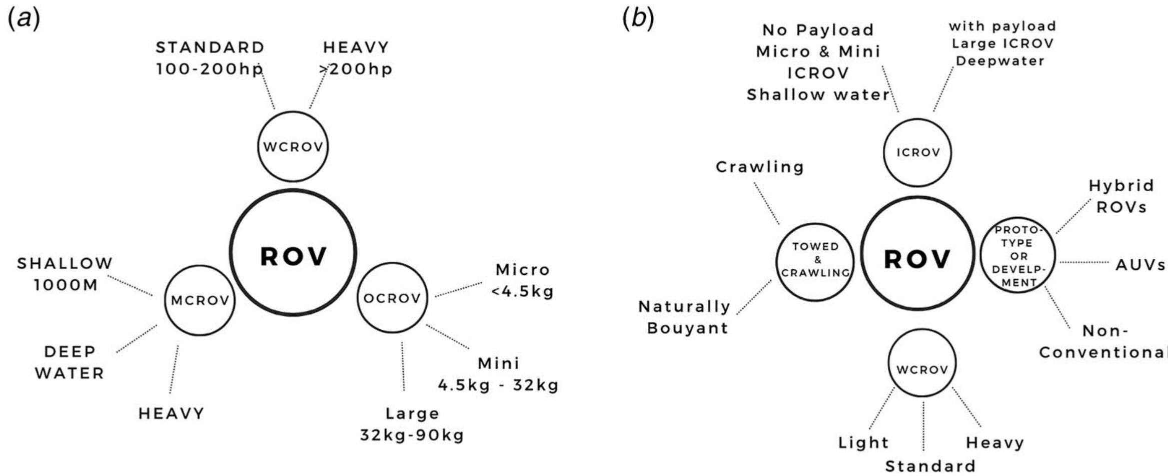

Fig. 2 Classification of ROVs based on the fourth approach

(3) Class IIB—observation class vehicles with light intervention/survey and construction capability.
(4) Class IIIA—standard work-class vehicles with a payload of ≤200 kg and through frame lift of approx. 1000 kg.
(5) Class IIIB—advanced work-class vehicles with a payload of ≥200 kg and through frame lift of up to 3000 kg.
(6) Class IVA—towed vehicles, typically plows used in subsea cable burial operations.
(7) Class IVB—tracked vehicles utilizing high pressure water jetting and specialized rock cutting tools, again used in the burial of subsea cables and pipelines.
(8) Class V—prototype or development vehicles.
(9) Class VIA—AUVs weighing ≤100 kg.
(10) Class VIB—autonomous underwater vehicles weighing ≥100 kg.

The new IMCA classification is an expansion of the old IMCA classification. Since we aim to condense and integrate, we will make use of the old classification. Based on the old IMCA classification, observation class remotely operated vehicles (OCROVs) class I and OCROVs class II have the same fundamental function of observation, and what differentiates them is the increased capability of class II because of the payload option and basic manipulative capability. The payload and basic manipulation are an accessory that may or may not be used on the OCROV, regardless of whether it is class I or class II. Hence, the option of a payload is a subcategory, which fits into the subcategory of the inspection class remote operated vehicle (ICROV) subcategories mentioned by Capocci et al. [20] and the observation class mentioned by Christ and Wernli [4].

Therefore, we provide a class named ICROV with two subcategories as shown in Fig. 2(*b*). The weight demarcation parameter is a strong constant regardless of the progress of technology and increased capability. However, the performance and depth capability criteria are weak because technology is rapidly catching up with larger vehicles. For this reason, medium size remotely operated vehicles (MSROVs) classification is not grounded. Because large MSROVs are categorized as vehicles that have a weight greater than 32 kg, the shallow and deepwater MSROVs can be categorized as large ICROVs with payload, higher depth, and more operational capabilities. The heavy MSROV as categorized by Christ and Wernli [4] utilizes both electric and hydraulic power, which is why it is often called a light working class remotely operated vehicle (WCROV). According to Christ and Wernli [4], WCROV has two subcategories: standard and heavy. Adding the MSROV often referred to as a light WCROV further merges the classifications and condenses the broad classification of the IMCA as shown in Fig. 2(*b*).

All ROVs have common components such as lights, cameras, thrusters, and other necessary electronics as shown in Fig. 1(*a*), but they can be differentiated by their uncommon components. For example, WCROVs use hydraulic power to drive moving components, either fully or partly, and they have a horsepower greater than 100. Some components may or may not be used in ICROVs, as shown in Fig. 1(*a*).

Demarcations are complicated on the subject of inspection/observation class and medium class ROVs as more advanced technology blurs the differences between these two. For example, medium-sized ROVs or light WCROVs can find themselves in the inspection category allowing for extra sensors and small tool skids to be added which may include the use of non-destructive testing (NDT) techniques to inspect the health of subsea offshore assets. Aside from basic camera visual inspection, inspection class vehicles can also carry out small tooling operations such as cleaning, latching, or recovery of items using manipulators and auxiliary equipment. Any class of ROV can be utilized for inspection, therefore classifying ROVs based on their purpose can be considered misleading, as there are compromises. Some inspections have to utilize a vehicle that falls into the WCROV to perform certain inspections.

Classes I, II, and III ROVs have the same body structure and principle of operation, while class IV (towed) ROVs have a completely different structure and principle of operation, and this class of ROVs are pulled through the water by a surface vessel to the desired location due to their limited propulsive power and maneuverability. On the other hand, class IV (crawling) ROVs have seabed locomotion and are used for trenching and burying cables.

As it can be seen, the current classifications of ROVs do not fit the rapid modern technological developments of ROVs and by extension unmanned underwater vehicles. Hence, there is a lack of distinctiveness between the ROV classes and types. There is a need for a classification taxonomy that will retain validity regardless of technological changes and advancements. The following paragraphs propose a new sustainable taxonomy.

In many ways, UUVs and unmanned aircraft systems (UAS) are alike. For example, in aviation, many authors have classified UAS as remotely piloted or autonomous systems. However, the same question of remote operation, true autonomy, and autonomy levels still exists [21]. One might ask if these vehicles are truly different or if it should be accepted across the board that there is no classification based on levels of autonomy and capabilities, but rather modes of operation that can be switched back and forth depending upon the requirement. For example, El-Sayed [21] stated, "Remotely Piloted Vehicle (RPV) or Unmanned Aircraft System (UAS) is an aircraft that flies without a human crew onboard the aircraft. There are a wide variety of Unmanned Aerial Vehicle shapes, sizes, configurations, and characteristics.

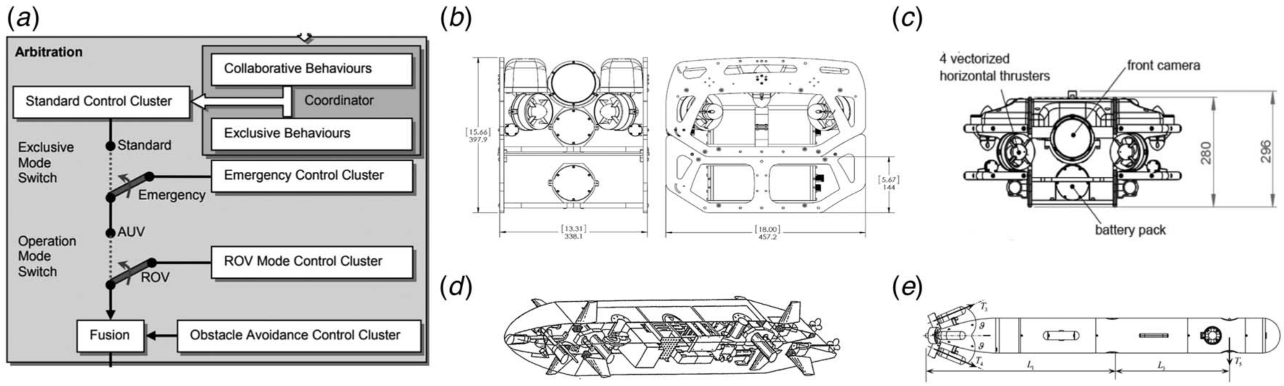

Fig. 3 (*a*) The operation mode switch is used to switch between AUV mode and ROV mode [23], (*b*) box-shaped open frame [24], (*c*) streamline-shaped open frame [25], (*d*) streamline-shaped closed frame [26], and (e) torpedo-shaped closed frame [27]

Unmanned Aerial Vehicles come in two varieties: some are controlled from a remote location, and others fly autonomously based on pre-programmed flight plans using more complex dynamic automation systems." Here the author uses the term remote piloted vehicle and unmanned aircraft system synonymously; this implies that autonomous UAS can and do belong to remotely piloted vehicles, while mentioning the two varieties, perhaps modes of operation, the author went on to mention remotely piloted and autonomous. The definition of an autonomous operation given by the International Civil Aviation Organization (ICAO) is "an operation during which a remotely-piloted aircraft is operating without pilot intervention in the management of the flight" [22]. Perhaps the vehicles have the same principle of operation albeit different modes of control. The question becomes: Is a mode of operation (control) sufficient to consider vehicles with the same operating principles as different classes?

The question of what connection remote operation and automation share arise; the basic definition of remote operation or teleoperation indicates the operation of a system or machine at a distance. By eliminating the human element, all UUVs and UASs are remotely operated systems. From another perspective, while autonomous machines, both underwater and air, are considered autonomous, they at the same time in many aspects are teleoperated. For example, in the automotive industry, most leading companies believe that to bridge the gap between current self-driving capabilities and the requirements needed for widespread adoption of autonomous vehicles, there is a need to have teleoperation capabilities for assisting self-driving cars, this is known as the teleoperation of autonomous vehicles. Teleoperation and autonomy are modes in which these vehicles can be operated, but it does not change the vehicle's class or taxonomy. With this foundation is in place, it becomes clear that autonomy and remote operation are modes of operation, and HROVs and AUVs can be seen as belonging to the same grouping, albeit belonging to different branches in a well-defined taxonomy.

Today some ROVs can operate in both teleoperated mode (ROV) and autonomous mode (AUV). ROV LATIS is such an example [23]. It is a next generation smart ROV with unique features, including multiple modes of operation, see Fig. 3(*a*). These types of vehicles are today classified as hybrid ROVs that were discussed in Sec. 4. To provide lucidity and distinctiveness to the subject of UUV and ROV classes, we present a classification taxonomy (or framework) based on frame structure and locomotion, see Fig. 4.

Within several ROV and AUV related publications, the authors have demonstrated that the lack of the tether requirement is one of the unique attributes of the AUV, for example, Newell and Gayathry [18] stated that "its design features hybrid functionality that enables it to operate in two modes: remotely piloted via tether or by battery power, operating autonomously and without a tether." Whitfield [13] stated, "Traditionally, an ROV was a tethered remote vehicle that needed to be brought to the surface for occasional recharging, while AUVs were untethered vehicles that could operate more freely in a subsea environment." Using this parameter to characterize ROVs and AUVs has not provided clarity thus far, mainly due to the rapidly changing nature of the UUV field, ROVs are already evolving to function without a tether with the introduction of the hybrid ROVs, that can function both as an ROV and AUV, tethered or untethered. Therefore, the presence of the tether, traditionally, is used as one of the criteria to differentiate AUV and ROVs, but this is already changing with the introduction of hybrid ROVs, which some researchers refer to as autonomous ROVs (AROV), as it was called in Refs. [28,29]. Hegde et al. [29] defined autonomous remote operated vehicle as tethered/untethered underwater vehicle, which can function autonomously. The tether as a criterion for ROV/AUV classification is thus weak. Even more so, in the future underwater wireless communication advances. However, classifying ROVs based on the frame structure and mode of locomotion will give a clear unambiguous classification framework for ROVs and the UUV family.

In Sec. 2, we wrote about the three modes of ROV operation: teleoperated, autonomous, and semi-autonomous. In the subsequent section, we demonstrated that this is not a sufficient criterion to differentiate AUVs from ROVs because ROVs can also possess autonomous capabilities and the emergence of hybrid ROVs, which can function in all three modes. This makes it difficult to classify. "It is a subsea vehicle, it doesn't matter as much"—Mr White, the vice president of subsea facilities engineering for Doris Engineering. Mr White implies that the naming AUV or ROV does not matter as much due to innovations [13]. Therefore, our proposed new ROV classification tries to address this by not trying to place too much focus and importance on what AUVs do and what ROVs do to differentiate them. Therefore, we will use the terms ROVs and UUVs synonymously. When it comes to underwater robots, the medium of communication can be tethered, untethered (wireless), or both. This provides the first branch of ROVs/UUVs. We further classified the ROVs based on their structure, which can be either an open frame, a closed frame, or a hybrid frame that can change its shape with actuation. Figure 4 shows our proposed ROV taxonomy and Figs. 3(*b*)–3(*e*), 5, and 6 show examples of the type of ROV frame structures.

Open frame ROVs can come in four varieties: towed locomotion, propelled locomotion, seabed locomotion, and hybrid locomotion, which is a mixture of two or more. A propelled open frame ROV can be seen in Figs. 3(*b*) and 3(*c*), and a hybrid locomotion open frame ROV can be seen in Fig. 5(*b*) with treads and propellers. Open frames are capable of full actuation and instrumentation unlike closed frames, and they can come in streamlined shapes (see Fig. 3(*c*)) and in aquatic pedestrian forms. Aquatic pedestrians are bio-inspired robots developed for walking and inspection in the underwater environment [35], an example of this type of robot can be seen in Fig. 5(*a*).

Closed frame ROVs can come in five varieties: towed locomotion, propelled locomotion, seabed locomotion, hybrid locomotion,

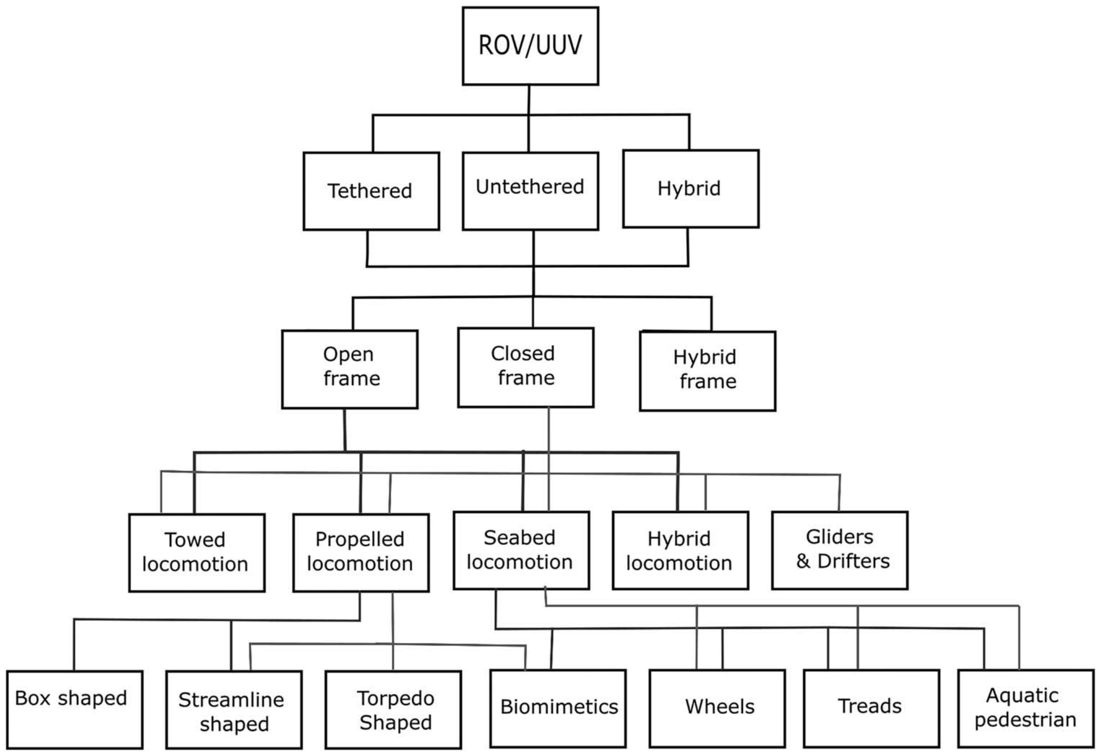

Fig. 4 ROV classification (towed branch on both sides)

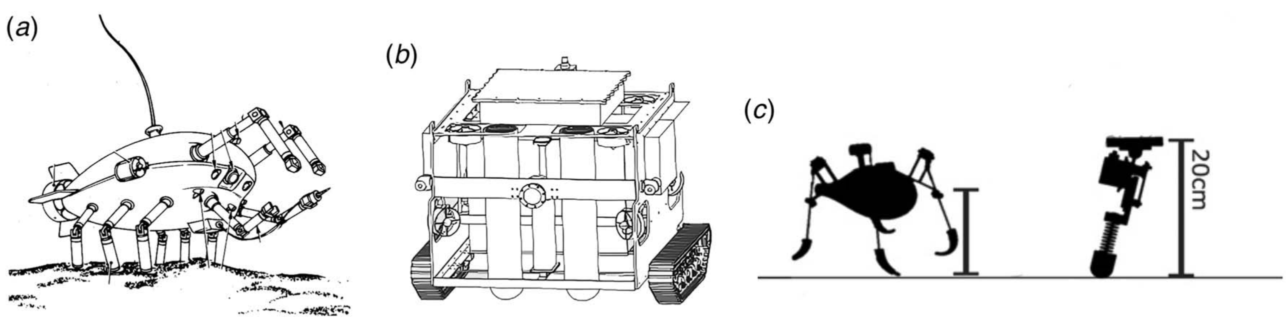

Fig. 5 (*a*) Closed frame seabed locomotion, aquatic pedestrian [30], (*b*) open frame hybrid locomotion, tread and propellers [31], and (*c*) example of biomimetics (left PoseiDrone, right one-legged demonstrator) [32]

which is a mixture of two or more, and gliders and drifters. An example of a closed frame can be seen in Figs. 3(*d*) and 3(*e*). Closed frame ROVs come in the same locomotion variety as open frame ROVs but with an addition of gliders and drifters, which generally come in a torpedo shape. Closed frames are generally not actuated or under-actuated, and this class can come in a torpedo shape (see Fig. 3(*e*)) or simply a streamlined shape (see Fig. 3(*d*)) and in the form of biomimetics (see Fig. 5(*c*)). To the author's knowledge, aquatic pedestrian ROVs are mainly closed frames thus far but open frames can also be in the form of an aquatic pedestrian. Aquatic pedestrians are more suitable for underwater inspections and observations in terms of their movement that generates very low turbidity compared to propelled and treaded ROVs, an example of an aquatic pedestrian ROV is shown in Fig. 5(*a*).

Hybrid frames ROVs are frames that can transition from a closed frame into an open frame using actuators. This first appeared in the aquanaut HROV and can be seen in Fig. 6(*a*). In 2021, it appeared as an autonomous underwater reconfigurable vehicle in Ref. [34], which can be seen in Fig. 6(*b*). Hybrid frames are capable of concealing the actuation for speed during travel, and revealing its full actuation on site for heavy-duty operations. Their subcategories may fall under open frame ROVs or closed frame ROVs depending upon their state as they can only assume one form at a time.

Our proposed taxonomy is unambiguous, yet it is not a hindrance to innovation. The lack of widely accepted standardized ROV classification was due to the transitional nature of the parameters and modes of operation of the vehicles. Because the classifications were made based on robotic inspection and intervention tasks, the technology is still maturing and facing new radical innovations that disrupt and blur previously accepted lines of demarcation differentiating the vehicles. For example, there is an emerging category of ROV termed fast ROVs (FROVs). FROVs are tethered to a surface vessel and can perform linear (pipeline) inspections at velocities of up to 7 km/h. They are designed to be flatter and less susceptible to drag than traditional ROV systems operating without a TMS via a smaller diameter umbilical (lessening system drag in deeper water). The tether also assists with functionalities such as launch and recovery, real-time data communications, and the ability to control the fast ROV to perform close visual inspection [36]. Radical innovations like these disrupt the current classifications. However, the classification provided in Fig. 4

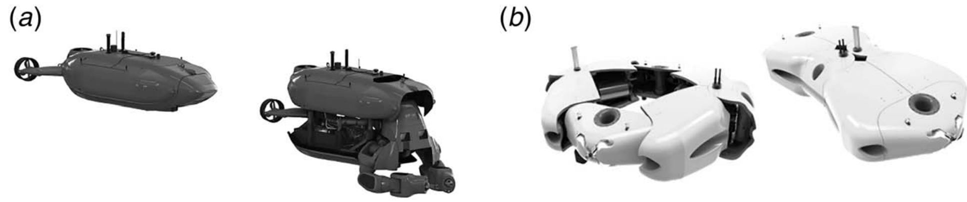

Fig. 6 (*a*) Aquanaut ROV [33] and (*b*) autonomous underwater reconfigurable vehicle [34]

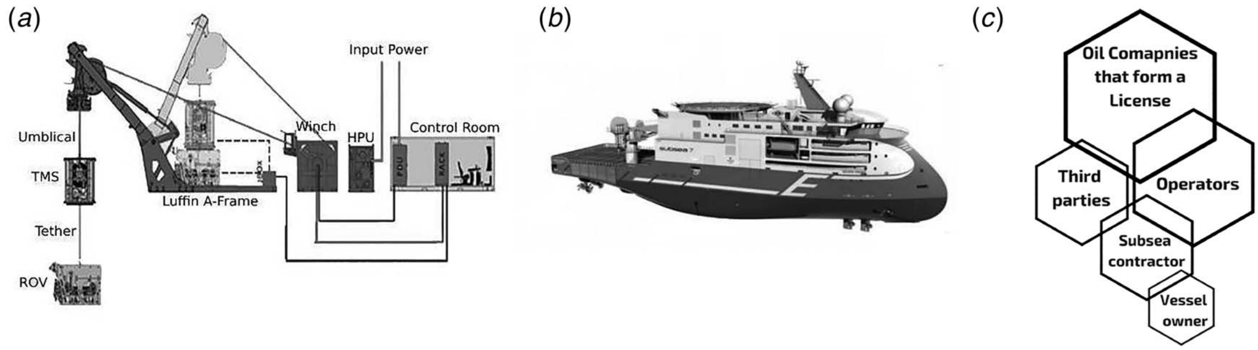

Fig. 7 (*a*) Traditional IMR operation setup [44], (*b*) IMR relationship between concerned parties, and (*c*) the relationship between the parties involved in IMR [45]

utilizes non-transitional parameters and therefore fits modern and future developments.

6 Inspection, Maintenance, and Repairs

Inspection, maintenance, and repairs is a term used for subsea intervention operations, and its objective is to facilitate safe and cost-efficient intervention on subsea installations to maintain a sustainable operation of offshore assets. It is industry driven by the need to keep costs low, spread financial and operational risk, and create effective ways for making new technologies available [37]. The inspection of subsea structures involves using a camera for visual inspection and NDT on the various structures to check for their safety and integrity [38]. Repairs and maintenance are carried out during the asset's lifetime [4].

Offshore IMR broadly comprises all IMR operations on subsea or floating structures across various industries: offshore Oil & Gas (O&G) industry, offshore mining [39], offshore wind farms [40], fisheries and aquaculture [41], civil engineering projects during installations [42], and ship husbandry [43]. This section provides an overview of the IMR in the offshore O&G industry.

Inspection, maintenance, and repairs operations used to be executed from floaters and modified supply vessels, but from 2008 to 2009 purpose-built vessels like the Subsea 7 as shown in Fig. 7(*b*), began to emerge [37] with the traditional IMR setup equipment (as shown in Fig. 7(*a*)) already installed. The setup consists of an ROV, a control command cabin or control room, a launch and recovery system (LARS), a TMS, and other options like object recovery system, see Fig. 7(*a*). The vessels have a dynamic positioning system, a satellite-based navigation system that locks the vessel into position at the site using powerful thrusters. Some of the vessels have moon pools in the middle of the hull where equipment can be lowered and hoisted. The vessel's crane is used to submerge the ROV through the moon pool. When submerged, they stay connected to the vessel via umbilical cables and the ROV pilots control the ROV from the control room. A crane known as the module handling system is fastened to the templates on the seabed and is used to retrieve and lower components to the seabed template.

6.1 Inspection, Maintenance, and Repairs Process. Subsea contractors carry out IMR operations. They hire a specialized vessel with the crew from the vessel owner or the shipping company [46]. Major operators, mostly, hire vessels on long-term contracts [47], usually all year round. Minor operators hire vessels on shorter leases. A single IMR vessel may have up to 70 people onboard belonging to up to five different companies [46]. From the point where the vessel begins transportation to the site, time is spent on regular maintenance of the vessel and preparation of operation. Upon reaching a site, usually near a fixed offshore installation such as a rig, the vehicle is held in place by a dynamic positioning system.

The primary interest of the oil company is the end product, and it serves as a client to the subsea contractor, who heavily relies on vehicles and systems to develop and provide the means of obtaining the end product safely and efficiently [48]. Therefore, the subsea contractor is not only involved with the IMR operations but in other areas that include: exploration and production (E&P), piper route surveying, provision of subsea facilities, and decommissioning.

The oil company operating the field does not make independent decisions. The "license consortium" assesses their needs and commissions the work that they want through the company operating the field [46]. Then the IMR operations department groups the IMR operations into tasks known as campaigns and many trips may be required to complete a campaign [46]. The campaign begins with the field operator preparing a work program that articulates the initial plan and scope of work for each field installation for the subsea operator, who then creates more specific plans known as the task plans; a subset of the generic procedure that defines the operational steps used during the operation. More than one task is usually carried out during the operation. The task plan is the document the crew are directly involved with in executing their operation. It contains a to-do list of items covering communication, technical safeguards and double-checks, safety checks and work permits, and a detailed description of the sequence and each physical step.

Every operational situation is unique and requires using the appropriate class of ROV with larger ROVs requiring more rigorous planning. Part of the to-do list in the procedures is to carry out a pre-dive and post-dive procedures. The pre-dive procedure includes crew briefing, vehicle preparation, and a pre-dive checklist. The post-dive procedure includes post-dive checklist and demobilization of equipment. Two hazard studies are carried out during the

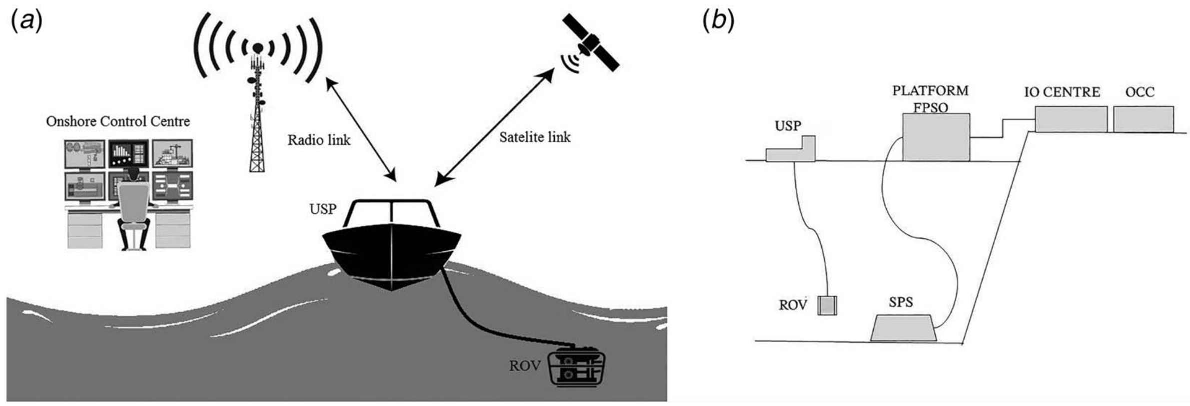

Fig. 8 (*a*) USP and (*b*) an illustration of an USP inspecting the SPS that is connected to the floating production storage and offloading that is connected to the onshore control center (OCC) [45]

operations: hazard identification (HAZID) and hazard operation (HAZOP). HAZID is carried out in the initial stage of the procedure to identify the hazard, after that, a HAZOP is carried out to remove or reduce the hazard that has been identified in the HAZID [37].

In summary, the license is the owner of the IMR operations department and therefore defines its priorities. They organize the resources and oversee the quality of service provided by the subsea contractor. Subsea contractors are known as prime contractors. They hire the IMR vessels from the vessel owners and are in charge of subsea operations on the vessel. Furthermore, the oil companies sometimes award contracts to specialized service suppliers known as third parties who may be present to join the subsea contractor on the vessel because of maintenance contracts for the equipment they supplied. The relationship between the parties can be seen in Fig. 7(*c*).

7 Emerging Methods of Inspection, Maintenance, and Repairs Operation

As demonstrated, the traditional way of carrying out IMR is cumbersome and expensive. Therefore, in the last few years, new IMR methods have emerged. The ultimate goal is intervention-free systems. However, with today's technology, this is not possible. Instead, the focus is on facilitating a system that can be maintained efficiently. An intervention-friendly design and smart solutions contribute to achieving this. This section explores the methods and analyses their strengths and weaknesses.

To be able to eliminate or reduce the use of support vessels in IMR, the solutions must utilize remote piloting, which is using real-time communication with low latency and high-speed broadband data communication to control the ROVs from onshore with a team, monitoring and intervening in operations as needed or a station situated on the seafloor, somewhere near the offshore assets. The challenge of remote piloting is signal latency but with a good communications link, and there is little to no difference between remote piloting and operating the ROV from the service vessel [49]. This is a viable option because a successful test of remote piloting a WCROV was carried out by Statoil in 2016 [24] with a 100% success rate. The emerging methods provided by companies and researchers around the world are unmanned support platform (USP), resident remotely operated vehicle (RROV), semi-resident remotely operated vehicle (SRROV), and drone remotely operated vehicle (DROV).

7.1 Unmanned Support Platform. Currently, this method utilizes a small unmanned surface vessel (USV) or autonomous surface vessel (ASV) as a carrier to transport, provide communication, power, launch, and recovery for an ROV (see Fig. 8). This reduces cost by avoiding the need for asset owners to keep a field support vessel on permanent hire. Companies are still working on full-size autonomous vessels, which are to be expected by 2025 [36,50].

British Petroleum has also publicly stated that 100% of subsea inspections will be conducted by maritime autonomous ships from 2025 [36]. Because this method is currently restricted to small ASV and USVs, in the literature the method is often called ASV/ROV or USV/ROV depending upon the work of the author. There is a lack of uniformity in the terms used causing a great deal of ambiguity in the literature regarding the terms USV and ASV [51] which can be explained by the vague and unclear boundaries between the levels of autonomy, but there has been an attempt at harmonizing and complementing these terms by Vagale et al. [50]. Noticing the ambiguity and lack of uniformity in the literature regarding this method, we aim to classify the method that utilizes an unmanned vehicle along with an ROV as an USP.

For the USP method to be successful, a correctly sized ROV must be used. A major challenge of this setting is the LARS and TMS. An ongoing research project between ASV Global and the University of Exeter considers the design and demonstration of an autonomous LARS [52]. An autonomous LARS is vital for the practicality of the USP method. Autonomous LARS design can be focused on an actuator (to raise and lower the ROV through the moonpool) or by using a cage (to launch and recover the ROV). Since this method eliminates cabin crew and all the costs associated with hiring a manned support vessel, it limits the technical capabilities associated with the traditional method. It limits the amount of ROV and tether weight, hence limiting the depth and tooling capabilities in the operation.

This type of setting utilizes a line of sight communications that is constrained by range or satellite-controlled systems that may have limited bandwidth and latency effects that can frustrate a vessel or ROV pilot which may add risk to sensitive operations. Furthermore, there is a varying degree of coverage and bandwidth depending upon the vehicle's location. There could also be a loss of connectivity due to weather, damaged equipment, or interference. Manual maintenance and supervision of ROV launch operations will also not be possible. Autonomous recovery will have to be used and it is currently a challenge requiring technical solutions because of real-time risks [36]. Automated tether management systems are used to mitigate this risk [52]. A good communication link ensures little to no difference between remote piloting a USP and operating the ROV from the service vessel. Several USP combination systems are emerging, such as the Hushcraft Sea-Kit system that has plans to develop an integrated ROV solution and others like L3ASV with their tested ROV prototype as well as several specialist systems from tier 1 contractors such as Subsea-7, Oceaneering, IKM Subsea, ECA Group, and SAIPEM, to mention only a few [36]. The use of USV or ASV to replace the support vessel is now gaining popularity as a growing number of operators are now requesting the use of this technology from their contractors to cut costs, due to its ability to retain data quality [53]. This method was used in pipeline operations support in Egypt, hydrographic survey in Alaska, long baseline array box-in and calibration, and acoustic Doppler current profiler data collection, and the ASV supported passive acoustics for marine mammal monitoring in the Gulf of Mexico [53].

7.2 Resident Remotely Operated Vehicle. RROVs are a permanent IMR installations offshore. Figure 9(*a*) shows a schematic of the RROV method. Its power, communication, and TMS are all setup offshore in different possible configurations of choice [55] as shown in Fig. 10. They have the capability of a non-stop operation, for example, the Oceaneering's resident freedom ROV has a SDS with the capability of conducting a continuous underwater operation for six months via a tether or a tetherless configuration. This setting is capable of performing surveys, inspections, valve and torque tool operations, and other manipulation activities with far more versatility and far less carbon footprint and mobilizations [49].

The SDS provides power and communication to the ROV and can range from a temporary installation with self-contained power to a permanent assembly using power and data connections from the field [54]. A buoy that is connected to the SDS is equipped with broadband communications, router, sim-cards, ethernet switches, and wave power generation capability. Some RROV concepts come in unconventional shapes such as the Eelume, a snake-like ROV vehicle concept developed for inspection and intervention in Ref. [56]. These types of rare ROVs fall under class V and biomimetics. There is also a similar design in Ref. [57] called an underwater swimming manipulator with supervised autonomy. Resident vehicles can perform a task that does not require the lifting capability of the support vessel and has the potential to reduce safety risk, the number of vessel days, lost production, and environmental impact. They provide a fast response time, which is very beneficial in emergencies and the opportunity to perform inspection and maintenance tasks more frequently [49]. However, they are not without challenges, and over time corrosion becomes a threat and the setting can only be used at the location where it is installed.

In an autonomous setting, the interaction between the vehicle and the subsea equipment determines the safety of the subsea asset and any failure from the vehicle could cause damage or harm to the subsea asset and production, hence an onboard decision support system and drift elimination are necessary. Hegde et al. [58]

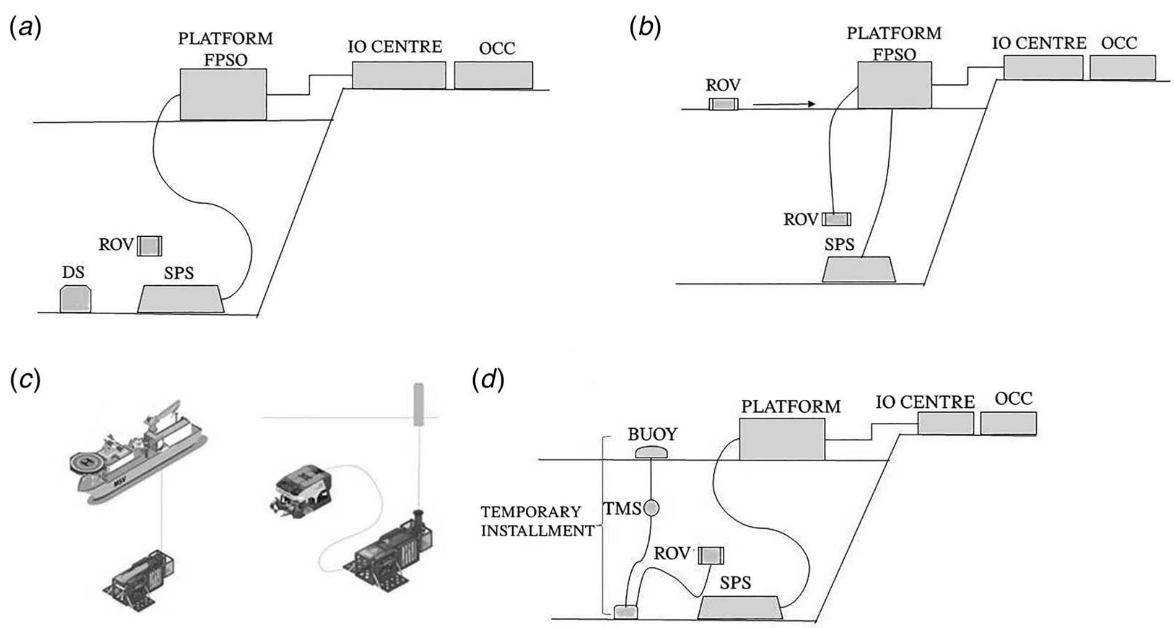

Fig. 9 (*a*) An illustration of the RROV method, (*b*) the DROV method, and (*c*) and (*d*) semi RROV deployment and operational modes [54]

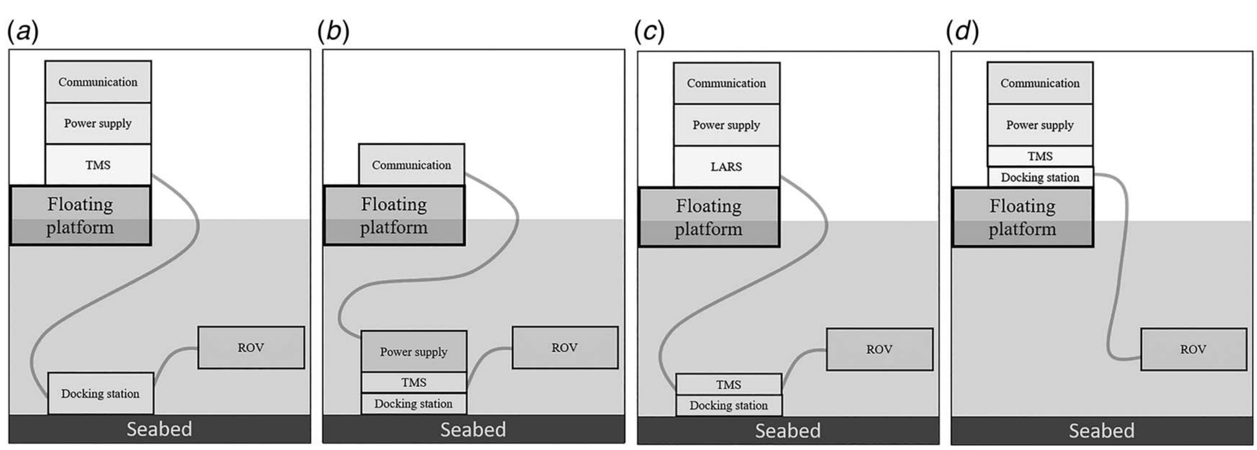

Fig. 10 Resident ROV system configuration. (*a*), (*b*), and (*c*) illustrates an arrangement where some components are submerged, and (*d*) illustrates the traditional setting where only the ROV is submerged [55]

Table 1 Comparison of methods

Methods	Reliability	Security	Implementation	Pros and cons
USP	It requires less mobilization time, hence, a faster response time compared to the traditional method. Carrying tools, which might be needed for a more advanced operation, is not possible. The mission will be jeopardized. Should the ASV/USV fail or go dead.	ASVs or USVs are small and visible on the water body, this poses a danger of theft, and it may also lead to some passersby picking up the vessel mistaking it for a lost vessel	Loss or reduction of communications tolerance, automatic tool changing, and managing operations in bad weather are some common and simple tasks made difficult when employing the USP method	Pros: Faster than the traditional method; cheap; no need for new equipment Cons: Technical capabilities limitation; no spare ROV; theft/piracy
SRROV	Fast response time when it has already been situated at the site but is slow if it has been decommissioned and has to be setup again, capability to harbor enough tooling on deck for all kinds of operations	There is little chance of theft or tampering by a curious passerby	The ROV and SDS system is already available. The only challenge with this method is the time and resources that it consumes before and after deployment.	Pros: Fast response when already installed; enough tooling; sufficient technical capabilities Cons: Expensive; no spare ROV; idle time
RROV	The response time of the RROV is fast because it is situated permanently at the site and is the most suitable option during emergencies	Little to no chance of theft or tampering by a curious passerby. There might however be a challenge with cyber security because there is a hacking possibility on the OCC.	The leap from work-class ROVs to resident systems is too large of a change There needs to be an installation of new equipment and tools on the seafloor near the SPS	Pros: Fast response; enough tooling; sufficient technical capabilities; no theft/piracy Cons: Expensive capital investment; new installments of subsea infrastructure; idle time
DROV	In the event of an emergency, the drone ROV is fast because it requires less mobilization but has lesser response time because it will need to transport itself to the site. Transportation of extra tooling will not be possible due to its moderate size and streamlined shape. In the advent of unexpected failure during transport or mission, the vehicle can be lost.	The vehicle must safely transport itself to the site. There is a low chance of piracy or unsuspecting passersby picking it up because it will either travel as a submarine or an airborne drone.	The technological building blocks for a drone ROV are already available and some companies like Houston Mechatronics Inc. are already paving the way for Drone ROV technology	Pros: Cheap; no need for new equipment installations; faster than the traditional method Cons: Slow response; limited tooling; possible loss of vehicle

presented an application of fuzzy logic for a safe autonomous IMR operation using visual-based pose estimation techniques and Tang et al. [59] also presented a vision system localization system that is capable of eliminating drift error using fuzzy inference. The concept of a vehicle as a permanent part of the subsea architecture enables a new level of asset management. The resident vehicle concept is exceptionally well suited to support future developments toward the subsea factory concept or in inhospitable geographical areas like the arctic regions and this requires autonomy. The next generation subsea inspection, maintenance, and repair operations [1] is focusing on technologies, algorithms, and methods required for enabling the right level of autonomy and human–machine interaction in IMR operations. This includes new perception, localization, path planning, and shared control technologies, as well as new methods for risk management. The next generation subsea inspection, maintenance, and repair operations have a strong focus on subsea factory design for autonomous intervention. The FP7 Project PANDORA on persistent autonomy has also been engaged in improving underwater vehicle autonomy significantly reducing the number of assistance requests [60] and successful tests were carried out in 2015 [61]. The RROV will be a valuable asset for future subsea infrastructures if it is designed to interface with the subsea asset. RROV eliminates the need for support vessels but possesses a high investment capital because of the need for new infrastructure and equipment to be installed permanently.

7.3 Semi-Resident Remotely Operated Vehicle. A semi-resident solution is appropriate in locations that are subject to adverse weather conditions, where having an RROV available 24/7 is highly desirable but there is no provision for a permanent RROV on site. Figure 9(*c*) shows a basic schematic of this SRROV method, a temporary installment that serves the purpose of an RROV. A semi-resident intervention campaign utilizes the same equipment as a traditional one. It includes the support vessel, equipment, and material, as well as the personnel required for the project execution to deploy the SDS and the ROV as shown in Fig. 9(*d*), but an enhanced remotely operated vehicle (EROV) is used in place of a traditional ROV.

The EROV is a battery-powered WCROV with a complete 4G LITE buoy and it is controlled from onshore with a battery capacity of 24 h. Since wireless communication underwater is still a challenge, the best option currently is the use of a 4G buoy [54]. The buoy connected to the subsea hanger via the mooring system also provides the dual purpose of providing power via alternative energy solutions, such as tidal power and wave power generators. Scheduled monthly visits are carried out to recharge the self-contained power storage garage and provide additional tooling if required. Since this approach uses a vessel to transport the self-contained EROV unit to the worksite for installation, this reduces the dependency on the vessel on site to support the IMR work scope, which also reduces the costs for the life cycle of the field [54].

Good communication is a key factor in enabling the EROV solution. For example, the North Sea is a prime area for the integration of EROV deployments due to the widespread availability of 4G networks. The cellular network provides high-bandwidth, low-latency connections that allow for the ROV to be flown remotely from an onshore command center and also for the provision of a backhaul link for offloading inspection data when required. The EROV solution is designed to fill the intermediate range of resident operations [54].

7.4 Drone Remotely Operated Vehicle. In the past and even in the present, some use the term drone to refer to ROVs [62–64], but we find the term rarely correctly applied. It is relatively the same with the misnomer; drone ships, a colloquial term. The word drone is an aviation term for unpiloted aircraft or spacecraft. unmanned aerial vehicles, for example, are commonly known as drones. A drone is flown from onshore, without the need for the traditional mobilization and transporting to the site (see Fig. 9(*b*)). In reality, we find that ROVs are transported to the site and launched from a vessel or platform at the site. In complex operations, a large vessel is used with large crews on deck to perform the ROV operations on site. However, an argument could be made that hybrid RROVs could be seen as drones. Nevertheless, these vehicles operate within the vicinity of the structures, but this could change in the future, whereby RROVs are utilized by hiring them to nearby offshore installments to reduce idle time and generate revenue. Nonetheless, drone technology in ROV operation is yet to be fully developed, and there have been projects by researchers and prototypes. In 2017, Wright [65] presented the SeaDrone, capable of carrying a sensor payload and a camera for scientific measurements. It can fly in the air (flown from shore) and in water (submerged), for close to shore and low depth, a continuation of this project was presented in Ref. [66] in 2019, and trials were undertaken in the arctic to investigate its sustainability for polar operation and to determine any necessary modifications.

In May 2018, Houston Mechatronics Inc. introduced an ingenious innovation called the aquanaut robot (see Fig. 6(*a*)). This robot can be launched from shore, which means it has eliminated the need for any vehicle for transportation to the site. It is a technological advancement powered by lithium-ion batteries with the capability of traveling 200 km to conduct offshore typical tasks. It has the capabilities of an AUV and ROV, meaning it is a hybrid ROV and can switch to AUV or ROV mode depending upon the requirement. It can travel in a submarine mode to the site where it can transform its body into a squarer block traditional shape of ROVs revealing its linear actuators, arms, and additional thrusters [33].

8 Comparison Between Methods

Based on the extensive literature conducted, the key considerations in the emerging solutions aimed to solve support vessel problems are these technological gaps and requirements; autonomy, reliability and security, field integration, communication, power, standardization, and navigation. A comparison of the solutions is given based on reliability, security, and implementation to extract the pros and cons of each method. These metrics are produced directly from the requirements.

The USP method is a small version of the traditional method with lesser technical capabilities, launch and recovery complications, and lack of onboard ROV maintenance capability, nonetheless a faster and cheaper method than the traditional method. Currently, the SRROV has more technical capabilities than the USP method and has a fast response time once installed on site. The DROV is an independent vehicle capable of transporting itself to the site to perform a task and back to its docking station. DROVs are relatively new and still under development but they will have a faster response time than the traditional and USP methods but slower response time compared to an already installed SRROV or RROV. However, DROVs can be used as SRROVs and RROVs installed temporarily or permanently near offshore structures in which case they can have a fast response time. RROVs require large capital investment but once installed it is the perfect tool capable to resolve the problems faced with traditional IMR operations effectively, efficiently, and it will be cheaper over the long run. See the comparison of the methods in Table 1. The HROV was not included because all of these methods can utilize an HROV to execute an IMR operation.

9 Discussion and Conclusion

The traditional method of IMR is cumbersome and expensive. It gets even more difficult to execute in harsh or arctic environments. For this reason, new methods of conducting IMR are currently emerging. We evaluated the emerging methods and categorized them into four, based on the configuration of the ROV system and the technology used, i.e., USP, resident ROV (RROV), semi-resident ROV (SRROV), and drone ROV (DROV).

The USP method is currently a miniaturized form of the traditional method, due to the small size and lack of onboard personnel, and this method has a limitation of technical capabilities and challenges of security and regulations. The RROV method is integrated into the offshore asset. Hence, it needs a high capital investment but it has the fastest response and is highly reliable. The SRROV method is a temporary installment of the RROV method with the support vessel having to install it and travel only to replace the ROV or recharge it until it gets decommissioned. The DROV method is a developing technology that can fly from onshore to an offshore site to operate without the need of a support vessel and new installment on the seafloor.

Based on the extensive research conducted, we find that the hybrid ROV (HROV) emerged based on the development of these emerging methods. We observed that the RROV is the most efficient and reliable method of conducting offshore IMR operations and when combined with the DROV, the method can solve the problem of idle time and generate revenue by providing services to nearby offshore assets. In the near future, a DROV could be used as an RROV (drone RROVs) and tools may be situated within the offshore asset. Subsea contractors can setup their drone RROVs near the subsea facilities where offshore facilities can simply pull up a robot for their IMR, this means remote assistance and monitoring and it is a move towards smart services, which is part of the industry 4.0 framework. This is the foreseen future of ROV IMR services. Once deliverance of data that is fit for purpose can be demonstrated through drone technology, the additional advantages will become self-evident.

We find that the lack of a widely accepted classification of ROVs (and of unmanned underwater vehicles) was due to the transitional nature of the parameters and modes of operation of the vehicles, which were used for the classification. The ROV classification, in general, was defined by grouping ROV functions and capabilities needed for generalized scenarios. The classification also placed too much attention on the mode of communication (tether and wireless) and operation (teleoperation and autonomy) and implied that these are parameters for classification. This type of taxonomy is unreliable or inapplicable for all ranges of vehicles, especially with the current technological developments. It is not adequate to capture the multifaceted nature of ROVs or UUVs and unmanned underwater operations. In the context of current modern developments and from observation of the actual practice, there is a need for a sustainable taxonomy for ROVs, and this paper has presented a taxonomy to contribute to the literature.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The authors attest that all data for this study are included in the paper.

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